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A METHODOLOGY FOR AUTONOMOUS ROOF BOLT INSTALLATION USING INDUSTRIAL ROBOTICS

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A METHODOLOGY FOR AUTONOMOUS ROOF BOLT INSTALLATION USING INDUSTRIAL ROBOTICS

THESIS

A thesis submitted in partial
fulfillment of the requirements for
the degree of Masters of Science in
the College of Engineering at the
University of Kentucky

By
Anastasia Xenaki
Lexington, Kentucky

Director: Dr. Steven J. Schafrik, Professor of Mining Engineering
Lexington, Kentucky 2021

ABSTRACT OF THESIS

A METHODOLOGY FOR AUTONOMOUS ROOF BOLT INSTALLATION USING INDUSTRIAL ROBOTICS

The mining sector is currently in the stage of adopting more automation, and with it, robotics. Autonomous bolting in underground environments remains a hot topic for the mining industry. Roof bolter operators are exposed to hazardous conditions due to their proximity to the unsupported roof, loose bolts, and heavy spinning mass. Prolonged exposure to the risk inevitably leads to accidents and injuries.

The current thesis presents the development of a robotic assembly capable of carrying out the entire sequence of roof bolting operations in full and partial autonomous sensor-driven rock bolting operations to achieve a high-impact health and safety intervention for equipment operators. The automation of a complete cycle of drill steel positioning, drilling, bolt orientation and placement, resin placement, and bolt securing is discussed using an anthropomorphic robotic arm. A human-computer interface is developed to enable the interaction of the operators with the machines. Collision detection techniques will have to be implemented to minimize the impact after an unexpected collision has occurred. A robust failure-detection protocol is developed to check the vital parameters of robot operations continuously. This unique approach to automation of small materials handling is described with lessons learned. A user-centered GUI has been developed that allows for a human user to control and monitor the autonomous roof bolter.

Preliminary tests have been conducted in a mock mine to evaluate the developed system's performance. In addition, a number of different scenarios simulating typical missions that a roof bolter needs to undertake in an underground coal mine were tested.

KEYWORDS: Mining industry, autonomous roof bolter, industrial robotics, coal mining

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December 8, 2021

A METHODOLOGY FOR AUTONOMOUS ROOF BOLT INSTALLATION
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DEDICATION

In honor of Xenakis family

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1.1 On Safety in the Underground Coal Mines

Continuous mining equipment is employed in underground room and pillar mines for the mechanical excavation of coal. Continuous miners are typically used in the construction of main access entries, gate road entries, and bleeder systems for longwall mining. The freshly extracted coal is then directly transferred to haulage equipment. In the eastern Appalachian region, the extraction or mining height typically ranges from four to ten feet. The ongoing mining processes often result in an unsupported roof that can fall under gravity forces. The unsupported roof can also be a result of the present in situ rock stresses. Hence, roof-bolters need to speedily provide roof and rib support through suitable bolts that secure the immediate roof rock layers.

Past research related to enhancing the safety of the roof-bolting operations shows that approximately 85% of the fatalities could be attributed to roof fall (Miller and McLellan, 1975; Helander et al., 1983). Drilling, volt-insertion, and tramming activities could also lead to an accident. Accidents have been reported involving the bolter itself as well as drill steel, boom, and automatic temporary roof supports. The majority of accidents were caused by human error. In addition, recent research studies have examined the exposure of roof-bolters to silica and coal dust underground. Studies by Ainsworth et al. (1995) show that these operators are exposed to the highest levels of silica dust, even higher than the continuous miner operator. Driven by the goal of making roof-bolting activities safe, the National Institute of Occupational Safety and Health (NIOSH) carried out research for automation of these activities at its Spokane branch. This involved the installation of position sensors on the machine for accurate positioning, communication, navigation, and guidance. Automating the roof-bolter was found to be the most challenging task (Schnakenberg, 1997). In 2008, Beck and Goodman (NIOSH) experimented with vacuum and mist drilling systems on the bolters. Dust levels in the ambient environment were compared by sampling the airflow. The vacuum drilling system was found to lower the dust concentration significantly when compared to the mist drilling system (Beck and Goodman, 2008). Investigation of dust exposures by NIOSH in mines in the southern Appalachian region have also showed the roof-bolter operators to be exposed to high dust levels. These studies also recommended that mines should minimize down-wind bolting especially in cases where the sampled dust showed high quartz levels (Pollock et al., 2009). NIOSH also carried out research on minimizing the dust emitted from the exhaust of the roof-bolter dust collection system. A wet exhaust conditioner was developed that forced the dust-laden air over a water surface. An airborne respirable dust reduction of about 41% was achieved in laboratory settings (Beck, 2012). NIOSH has also designed a novel canopy air curtain to lower the roof-bolters' dust exposure. Computer modeling followed by laboratory tests on reduced and full-scale models, have shown effectiveness. Statistically, reductions exceeding 67% were realized in the laboratory tests (Listak and Beck, 2012; Reed et al., 2017). Experiments at NIOSH with a bit sleeve device and dust-hog-type bit combination were also found to lower dust escaping into the ambient atmosphere by about 50%.

Not only is the bolter operator exposed to roof falls and elevated dust levels, the drilling and bolting processes are often noisy. MSHA coal mining data acquired in 2005 indicated roof-bolter operators to be continuously exposed to noise over prescribed threshold limits. The noise could also trace its origin to several pumps mounted on the roof-bolter. The bolter operators adopt a variety of personal protective equipment to shield themselves from continuous noise. NIOSH developed chuck and bit isolators and showed that when these are used together, they could significantly lower the noise pressure levels (Michael et al., 2015). A suite of instruments developed by NIOSH including the bit isolator, the chuck isolator and a collapsible drill steel enclosure working in tandem could lower the sound pressure levels by 13 dB(A) (Lowe et al., 2010). Field tests of the drill bit isolator developed by NIOSH in collaboration with Kennametal Inc. and Cory Rubber Corporation showed that a noise reduction of 3-5 dB(A) can be achieved. These were also found to be durable with five of the nine devices tested exceeding 610 m (2,000 ft.) drill depth (Azman et al., 2012). In 2011, NIOSH developed elastomeric isolators that break the continuous contact between the drill steels. Laboratory tests showed a noise reduction while drilling by 3.7-6.6 dB (Michael et al., 2011).

1.2 On Mechanization of the Roof-Bolting Cycle in the Underground Coal Mines

During the last decades, the use of roof-bolters to reinforce the underground mine roof has been growing steadily. roof-bolting practices have become the primary support system in underground coal mining. The roof-bolters drill holes into the roof and install roof bolts to support the roof. Nearly all underground coal mines in the USA are mined under roof-bolted roofs. The majority of roof-bolters in underground mines are manually operated. The operation involves the following steps:

(i) The operator places the drill steel into a dedicated drill head. By operating a manual control, it drills the hole to the roof, and the then removes the drill steel.

(ii) Then, a bolt inserter (wrench) is typically placed in the drill head, and a roof bolt is placed in the bolt inserter.

(iii) Next, the operator installs the bolts by operating manual controls.

This process is highly labor-intensive and relies heavily on the operator's judgment. roof-bolter operators are exposed to hazardous conditions due to their proximity to the unsupported roof, loose bolts, and heavy spinning mass. Prolonged exposure to these risks inevitably leads to accidents and injuries. For these reasons, the mining sector is currently in the stage of adopting more automation, and with it, robotics (i.e., **Figure 1.1**). One of the latest trends in recent years is the development and utilization of autonomous equipment. This is particularly prevalent in many fields of engineering and scientific applications, including mining. Some applications include intelligent transportation (Zhang et al., 2011), agriculture (Li et al., 2009), marine and planetary environment exploration (Leitner, 2009; Wynn et al., 2014), mining (Marshall et al., 2008; Lösch et al., 2018), and disaster reconnaissance and rescue (Olmedo et al., 2020).

This study focuses on developing a robotic assembly capable of carrying out the entire sequence of roof-bolting operations in full or partial autonomous sensor driven rock bolting operations to achieve a high-impact health and safety intervention for equipment operators.

Figure 1.1: In a mining site, autonomous bolters can accomplish complex tasks, such as roof support and protection from falling debris. Remotely, in a command central, specialized humans supervise all the actions and intervene if necessary. Image retrieved from Bathopele Mine 2020.

The automation of a complete bolting cycle of drill steel positioning, drilling, bolt orientation and placement, resin placement, and bolt securing is discussed using an anthropomorphic robotic arm. The bolting cycle as a part of the drill-and-blast mining cycle is shown in **Figure 1.2**. A human-computer interface is developed to enable the interaction of the operators with the machines. Collision detection techniques is then implemented to minimize the impact after an unexpected collision has occurred. A robust failure-detection protocol is developed to check the vital parameters of robot operations continuously. This unique approach to the automation of heavy tool handling is described with lessons learned. The concept of change is quite broad and introducing a new technological mind-set will always remain a challenge. According to Hattingh and Keys 2010, modernizing the industry entails two components:

(i) Introducing machines and automation into mining operations (mechanization); and

(ii) changing the culture of the people from every level, who are involved from planning to everyday operations (human factors).

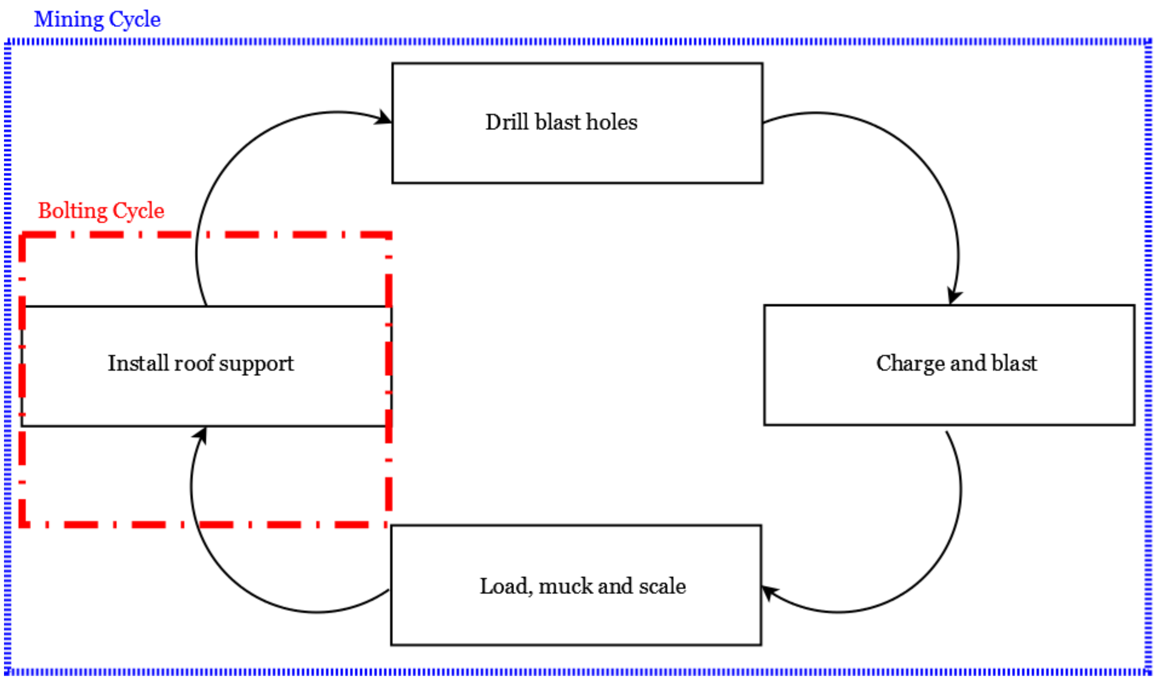


Figure 1.2: The underground conventional drill-and-blast mining cycle and bolting cycle.

Both elements will be covered in the research presented here, although more emphasis will be given to the mechanization of the roof-bolting-cycle. Based on Jackson et al. 2010 , a systems approach can be classified into four stages which are directly linked to the systems engineering process:

(i) System Analysis (or Conceptual Design Phase): during this stage, the initial concept for the new mechanization process is defined. The objectives of the user's needs and system performance and requirements are to be specified. Studies will be undertaken in the mine to acquire the field observation data and a preliminary research and development efforts will be initiated.

(ii) System Design (or Preliminary Design Phase): during this phase, the functional analysis and synthesis of the system is being conducted. A set of detailed working specifications are drawn from the preliminary system design for the new system (analogical comparison). Subsystems and components are to be developed during the Systems Design phase of the project. In this stage, it is important to identify potential errors and problem areas. Those malfunctions must be addressed to optimize the overall system performance, cost, and other factors.

(iii) System Implementation (or Detail Design Phase): this stage incorporates the completion of the system design. A new or redesigned machine is being developed (prototype system development). A final testing and evaluation process will ensure if the product is performing successfully.

(iv) System Operation (or Production Phase): during this state, the system needs to be tested on a routine basis on the environment that is being proposed to operate (systems are often developed and designed in different environments). If the results are unsatisfactory, re-optimization is required. When the system evaluation is completed and the specified objectives are reached, the newly modelled system is given to production.

1.3 Research Objective

Sustaining the rock mass within the proximity of the excavation after blasting is crucial in order to decrease potential hazards associated with rockfalls, and rock bursts. As reported by Ferreira and Minova 2012, falls of ground (FOG) remain the main contributor of fatalities in narrow reef stopes. Equipment operators, especially, roof-bolter operators are often exposed to dangerous conditions. The risk increases due to their proximity to the unsupported roof.

Dust and noise exposure due to rock drilling and bolting should not be discounted. Roof-bolting has been the principal means for enhancing miner safety regarding preventing different roof falls in underground coal mines in recent decades. This research focuses on the development of automated processes within the roof-bolting cycle with the ultimate goal of removing humans from hazardous environments. The only human interaction with the autonomous roof-bolter should be re-provisioning the onboard storage, maintenance and supervisory control of the machine (Jobes, 1990).

A detailed study of human motion is first being carried out using sensors and computer software. Computer simulations are set up to design the trajectory of the anthropomorphic robot. The trajectories are then optimized using various techniques to customize them for mining environment conditions. A replica of the roof-bolter module and the software controlling the robotic arm is built and tested. The trajectory is then, is being adopted by the robot. The robot can now obtain information about position, orientation and speed. A human machine interface is being integrated to enable the manual approval of the tasks and to override the system in the event of unpredicted or unsafe actions. This robotic system is being deployed and fully tested in the laboratory environment located in the Mining Engineering Department, at the University of Kentucky, US. In line with the aforementioned objectives, the following research questions can be asked:

(i) What processes or methods will be used for the development of the autonomous roof-bolting cycle?

(ii) What criteria will be used to validate the reliability of the autonomous roof-bolting cycle?

The objective of the research will be to evaluate whether a system engineering approach may enhance the level of safety of roof-bolting in underground coal mines. The research is focused on a single piece of equipment, the roof-bolter.

1.4 Significance and Contribution

The author proposes developing a robotic assembly capable of carrying out the entire sequence of roof-bolting operations autonomously. To achieve that, a detailed study of human motion is first carried out using sensors and computer software. Computer simulations are set up to design the trajectory of the robot. These trajectories are optimized using various techniques to customize the robot for mining environment conditions. A replica of the bolter module and the software-controlled robotic arm is built and tested. The trajectory is adopted by the robot and includes vital parameters like position, orientation, and robot speed. A human-machine interface is integrated to enable manual approval of the tasks and over-ride the system in case of unpredicted or unsafe actions. The robotic arm is deployed and fully tested in the laboratory environment. The above processes are iterated for refinement before the final deployment of the robot in a mining environment.

1.5 Research Delineation

The framework of this study is strictly based on a system engineering approach and systems engineering tools previously used in various industries. It will be adapted to roof-bolter implementation in an underground coal mine in the state of Kentucky, U.S.

1.6 Thesis Outline

The document is structured as follows:

Chapter 2 will cover a brief literature review around mechanization and its challenges as well as a brief overview of the considerations for the development of the automated roof-bolting cycle.

Chapter 3 will deconstruct the opportunities and challenges involved in implementing the autonomous roof-bolting operation in underground coal mines, based at the University of Kentucky, U.S., Mining Engineering lab.

Chapter 4 will cover the basic concepts and the proposed approach followed for the realization and the development of the autonomous roof-bolter regarding the laboratory scale setup build for simulations.

Chapter 5 presents the evaluation and results of the tested embedded support systems used in the project.

Finally, Chapter 6 will conclude and summarize the research, and then provide recommendations for future work.

1.7 Summary

A background leading to the importance of the research was provided and the objectives of the research were identified. The major impact of the research was given through its significance and contribution, and the contents of the upcoming chapters were also briefly outlined.

Chapter 2 Literature Review

2.1 Introduction

Automation in the mining industry is not a novelty. Robotic and Autonomous Systems (RAS) are already playing an essential role in today's mining industry. The mining industry is currently in the stage of adopting more automation, and with it, robotics. The purpose of this chapter is to gather information on the concept of automating mining equipment to move miners away from the dangers roof-bolting creates. A significant emphasis of this research is reviewing mining technology that improves roof-bolter productivity and fosters safer, more sustainable working conditions for miners. Specifically, the construction of an autonomous robotic manipulator hand depends on developing robust remote calibration diagnostics and a self-monitoring system, the configuration of the robot-specific remotely triggered actions, optimized plan and control techniques, and the integration of the robotic spatial perception. Moreover, various considerations need to be made when developing and installing communication systems, because the underground mine infrastructure may affect the signal transmission and propagation.

This chapter describes a systematic approach to automation problems with integrated automation solutions (systems) based on Programmable Logic Controllers. The primary purpose of solving an automation problem is to develop a solution that does not impose the desired behavior on the controlled system. At the same time, a proper application of automation must meet other criteria, such as the following:

(i) Be economically feasible in principle as a cost for the initial construction and installation of the solution. In addition, the maintenance cost must be included in the implementation cost.

(ii) Be safe for operators and the environment.

The typical steps in the process of developing integrated PLC automation solutions are as follows:

(i) Description of the automation problem.

(ii) Identification of the signals and parameters involved.

(iii) Description of the automation solution.

(iv) PLC connections and programming.

Each step involves processing the information from the environment and constructing a part of the integrated solution. At the same time, each step includes the corresponding complete documentation to be transmitted or registered for future use. In the general case, the formulation of the automation problem consists of two interrelated parts:

(i) The reporting and recording of critical physical parameters (i.e., the temperature of a room, the level of a tank, the current flowing through a coil) are of interest for the specific application for which the automation is intended.

(ii) The description of the desired behavior of these physical parameters (i.e., their values are kept within defined limits required for the safe operation of the associated machines).

The literature will, therefore, be gathered into the following main topics: 1) The various challenges addressed by multiple authors related to the mechanical design around mining automation systems currently in use; 2) the automated equipment available in existing coal mines, their benefits, capacities, specifications, etc.; and 3) the study of the human-machine interaction.

Furthermore, selecting the anthropomorphic arm and ways to trigger and operate it are significant in this review section. Extensively, the main topics are 1) the benefits and challenges of selecting the industrial manipulator; and 2) the study of triggering the industrial manipulator during an emergency.

2.2 Re-imagining the Future of Mining Processes

Miners still use heavy machinery, such as explosives, trucks, drills, and bulldozers, especially when they dig deep into the earth. However, advances in technology have allowed miners to excavate with more accuracy and less harm to the surrounding environment. More efficient machinery can also reduce energy consumption and improve the number of minerals or metals gleaned from the shaft. Thus, mining is no different from other sectors in that automation is often primarily driven by making equipment operator activities safe by removing humans from a hazardous environment and increasing operational efficiency and production capability. Today, mining is taking advantage of lessons learned by other sectors and industries.

In current times, many mining companies have begun their digital ventures toward intelligent processes, seizing the future of mining operations. That implies introducing new technologies and considering what role these technologies will play and what jobs will look like in a company that assimilates these novel technologies. Emphasis has been placed on autonomous equipment solutions that can significantly improve miners' safety and working conditions. Namely, embedded intelligence systems enable mining equipment to robustly navigate the prescribed path (production areas) and accomplish designated tasks. Other intelligence systems in mining include robotized technologies, machinery, and mechanisms with the elements of artificial intelligence, as well as mining and transport system automatic controls. Of significant interest has been the establishment of fundamental objective laws of the interoperability of mining engineering systems employing industrial robots with the natural human environment in the mining engineering system and in the affected area. Virtual industrial robotic solutions are also being studied with the introduction of Industry 4.0. Flow charts 2.1 and 2.2 show an example of all technologies incorporated into the design of autonomous mining equipment.

2.3 Industrial Field Networks

Industrial computer networks are subcategories of local computer networks with specific requirements and specifications. They are characterized by the handling of small volumes of data with predictable transfer speed and reliability. The common point of data transfer in field networks is a twisted pair of cables, which simultaneously carry a

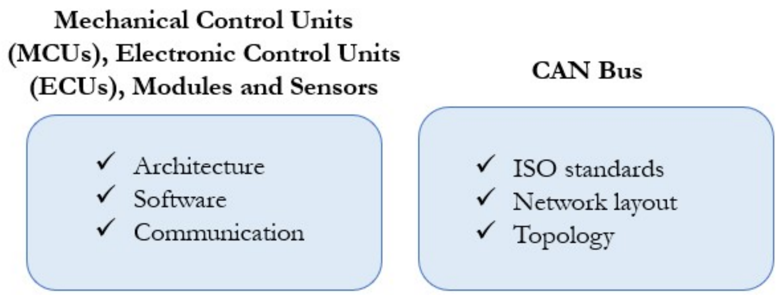


Figure 2.1: Implementation of MCU, ECU, modules, and sensors on CAN Bus

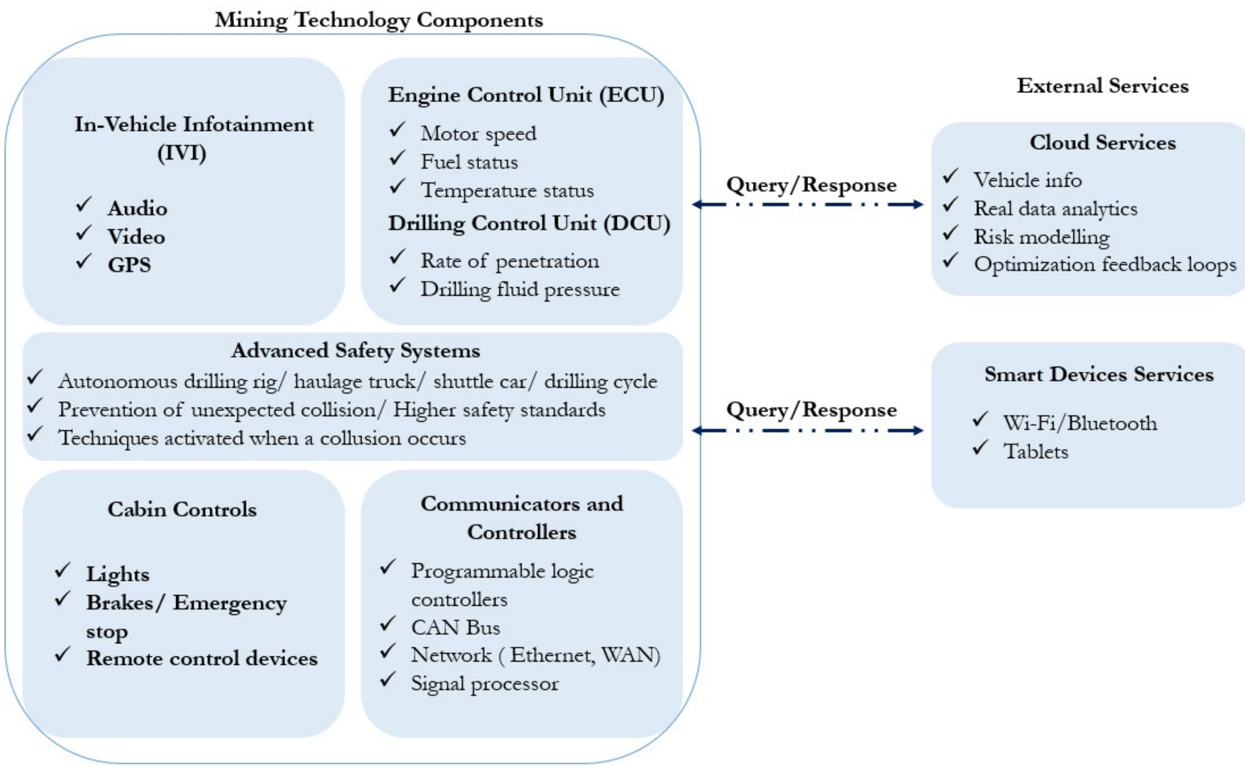


Figure 2.2: Autonomous technologies in mining

digital signal and a DC power supply. At the end of each part of the network, there is a terminal resistor that recognizes signals from the interfaces of the network devices. In field networks, all computing power is distributed to the interconnected controller processors and not to a central point. Field controllers follow specific communication protocols. These protocols allow for control the interconnection, communication, and transfer of data between devices. Protocols determine the type of equipment and software used. In field networks, there are two basic models in the way information is transmitted between network devices:

(i) The client-client model, a network device that provides data services when another network device requests specific information. The client makes a request, and the server returns a response, or a series of actions are followed. The server can be activated immediately for this request or add the request to a queue and is adopted by network protocols such as Modbus, PROFIBUS-FMS, WorldFIP, INTERBUS, and P-NET.

(ii) The publisher-subscriber model, in which some publisher nodes produce available information on the network. Subscribers listen to the specific nodes that provide the information. This model offers greater scalability compared to the server-client model due to the existence of multiple parallel publishers and is adopted in protocols such as WorldFIP, Foundation Fieldbus, CAN, CAN open, Device Net, Control Net, KNX, and Lon Works.

This study focuses on the use of a CAN network protocol, which is found in integrated mining automation systems.

Characteristics of CAN protocol

The Controller Area Network (CAN) protocol is a carrier sense multiple access protocol with collision detection. All CAN transmissions are broadcast in nature, which means nodes receive all the transmissions on the CAN Bus. Bus arbitration, i.e., the resolution of which message gets transmitted next if a collision occurs, is decided by the message priority. Priority is selected based on the so-called identifier field in the message header. A lower identifier corresponds to a higher priority, which means messages with lower identifiers will be transmitted earlier than messages with higher identifiers if both are ready to be sent in the transmission buffer or if arbitration is triggered by collision during the transmission.

Each message transmitted using the CAN protocol is accompanied by 11-bit authentication fields, which do not relate to the message information but are used as control fields, which indicate who is transmitting to whom or what, what kind of message is being sent, and with what priority. The CAN message packet starts with the total Start of Frame (SOF) with 1 bit and follows the standard identity or arbitration field, with 11 bits, which determines the message's priority. The structure of a CAN message is illustrated in **Figure 2.3**. It has the following important fields:

(i) Identifier: It represents the priority of a message. A lower-value identifier indicates a higher priority on the CAN bus.

(ii) Data Length Code (DLC): It represents the length of the data field in a CAN message.

(iii) Data: Data is the actual payload of the message. A total of 64 bits of data can be transmitted in the message.

(iv) Cyclic Redundancy Check (CRC): This field contains the checksum of the data field for error detection.

(v) Acknowledgment (ACK): The ACK bit is used to check the integrity of data. The receiving node overwrites the recessive bit to the dominant bit for an error-free mess- age. In the case of any error, the recessive bit is not overwritten, and the sending node retransmits the message.

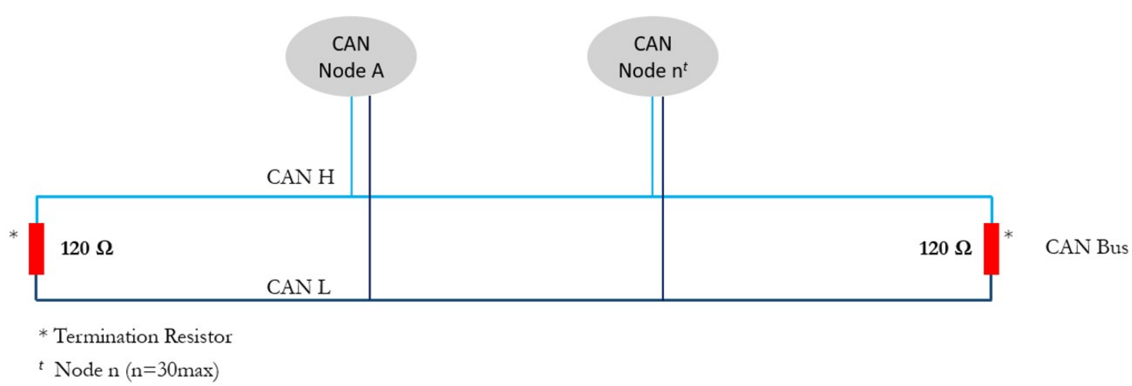


Figure 2.3: CAN Bus network topological basic structure, based on Al-Aani (2020)

CAN is a serial data communication protocol with high performance, reliability, ease of development and a low-cost field bus. It consists of CAN H and CAN L lines; the transmission medium can be an unshielded twisted pair, cable and fiber, the communication can rate up to 1Mb/s, and its transmission can distance up to 10 km (Li et al., 2017). Every ECU transmits and receives data over the same lines. The CAN Bus is commonly used in embedded control applications, including in mining equipment controls. By switching to CAN-bus architecture, electrical components can be daisy-chained, which dramatically reduces the amount of wiring required on the vehicle. **Figure 2.4** shows a generic CAN bus configuration of the studied roof-bolting system.

CAN networks are often divided in different subnetworks according to their function and specific needs, such as high-speed CAN (CAN-C) for motor management, and low-speed CAN (CAN-B), for climate control. As a result, a major part of information about the inner workings of a vehicle can be learned by examining CAN bus traffic. Users can now navigate through display screens to gather status information on how the engine is running, as well as error messages, more efficiently and intuitively. This information is useful to track driver behavior, the status of equipment, etc.

How does CAN communication work?

In a CAN Bus system, multiple nodes communicate with each other through transmitting messages to target nodes based on specified identifiers. All nodes function as masters. This configuration means there is no master controller that supervises the bus. This configuration ensures more robust connection as well as fault reduction. The bus network topology of the CAN Bus reduces the points of failure since a single data line is used to handle all communications. Furthermore, nodes branch out from the main line; this means if one node fails it does not affect any other nodes in the system nor does it affect the functionality of the main bus. Such topology makes it easier to monitor faults and diagnose specific problems, rather than having to manually query numerous sub-controllers distributed throughout the system. CAN protocol includes bit wise arbitration messages that are arbitrated through the ECU- priority embedded controller. Transmitted messages are not assigned from one node to another, instead, all units on the network communicate with each other.

This arbitration structure in the linking system allows high priority messages to be transmitted before low priority messages; it also prevents time delays (Etschberger, 2001; Pfeiffer et al., 2008).

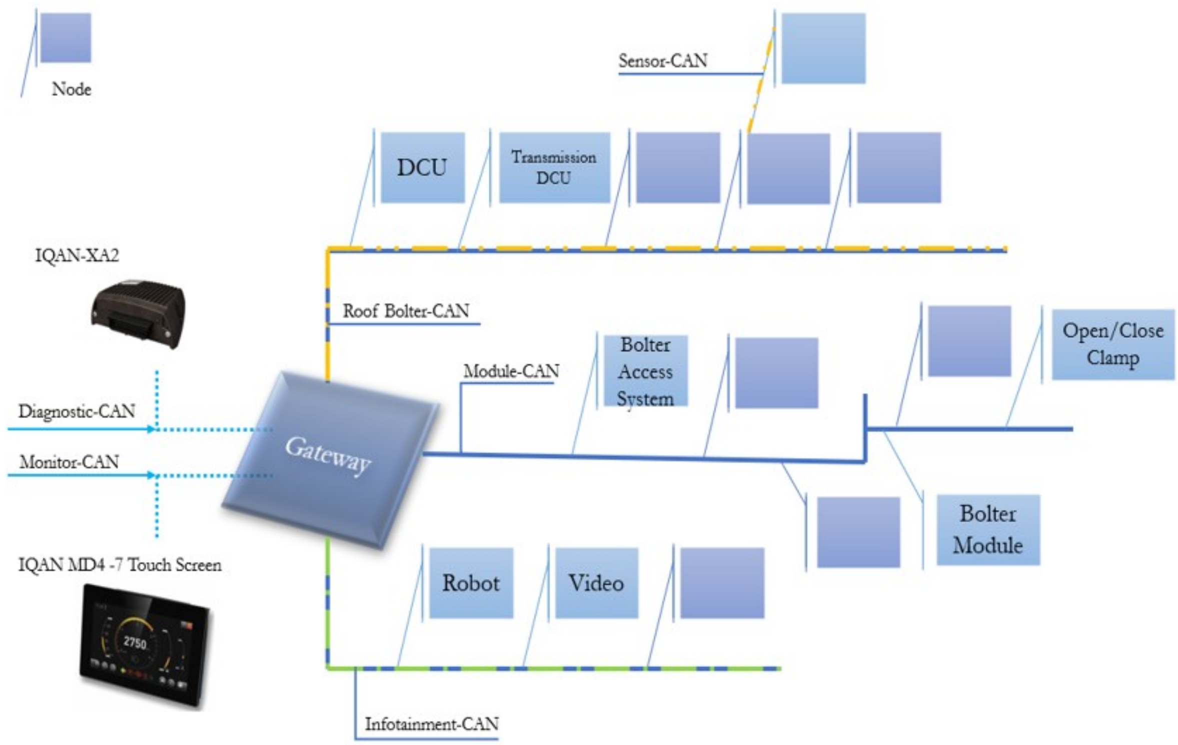


Figure 2.4: Generic model of a roof-bolter CAN bus. Multiple sub-networks with different functionalities are interconnected through gateways

Benefits of CAN Bus system

There are benefits of using the CAN bus as a serial communication protocol, particularly in reducing wired interconnections in a vehicle. Some of the benefits in implementing the CAN protocol in automobiles are:

(i) Reduced wired interconnections,

(ii) low-cost implementation,

(iii) speed, reliability, and error resistance, and

(iv) worldwide acceptance

2.4 Autonomous Mining Equipment

Automation is currently being utilized in nearly all phases of mining including extraction and drilling. Some examples are presented in the following paragraphs. For example, LASC Longwall Automation technology has been used to increase productivity in underground mines and to remove the employees from exposure to high respirable dust levels (Tyuleneva et al., 2021). Other examples include the use of autonomous haul and dump trucks to transport materials in mines. Scheding et al. (1999), using results of field trials conducted in an underground mine in Queensland, Australia created a navigation system capable of making large heavy industrial machinery much safer and more efficient in uneven terrain. Roberts et al. (2002), introduced the term opportunistic localization, a technique that allows the vehicle to make appropriate decisions when driving through intersections. This implies that the vehicle is travelling while knowing the segment of the route and at the same time identifying the next node. Larsson et al. (2006) proposed a fully automated navigation system using the fuzzy behavior-based approach to navigate underground Load-Haul-Dump (LHD) vehicles. Additionally, Marshall et al. (2016) presented an automated way to load materials using draglines and shovels.

2.5 Robotic Miners

Automation capabilities continue to increase as a result of advances in machine sensing and vision which aids in balancing the scales between humans and machines. Hardware and software advances have greatly expanded the opportunities for adopting automation to many human-machine systems, resulting in much more complicated decisions about choosing levels of automation for different machine functionalities. The mining industry is currently in a stage of adopting more automation, and with-it robotics. The area of development being researched, which concerns the content of this review, includes the automated installation of ground, roof, and rib supports, as well as robotic rock cutting machines.

Localization

The underground environment in miners is particularly challenging when it comes to improving positioning accuracy. Several methods have been proposed to address this problem in the longwall context. One method is based on measuring the three-dimensional shearer path directly through an inertial navigation-based system (Billingsley and Brett, 2015). Xu and Wang (2010) implemented a shearer working path system based on three-machine position and dynamic-static fusion. This approach collects dynamic data of the shearer, static data of the conveyor shearer, and data from the hydraulic supports, in order to acquire the shearer's three-dimension location information.

Horizontal position information is collected using the Inertia Navigation System (INS) technology (Reid et al., 2011).This system provides high short-time accuracy and robust autonomy, but it shows increasing error growth over time (Ruiz, 2009). To solve this problem Fan et al. (2014) developed the wireless sensor network. Even though their approach showed a decrease in the position drift error, the position coordinates of the anchor nodes could not be determined in an accurate manner because of the movement of the roof support system. Wang (2022) installed tilt sensors on the shearer body and armored face conveyor (AFC). The main disadvantage of this method was that it demonstrated one-dimensional positions of the shearer instead of three-dimensional positions. In yet another approach, Wang and Wang (2020) used a shearer positioning system based on an INS and added an axial encoder, which was used to calculate the shearer's moving trajectory. They also used shearer motion constraints to improve the accuracy of positioning.

Navigation of commercial Automated Guided Vehicles (AGVs) is currently accomplished through inertial navigation, magnetic navigation, electromagnetic navigation, lidar navigation, visual navigation, as well as other navigation methods. Localization methods that are available on AVGs, to include laser triangulation methods, ceiling mounted bar codes, range, or camera-based wall-following, using floor markers or magnets as guidance while the vehicle updates its exact location as it follows the magnetic tape. Houshangi and Azizi (2006) integrated the robot's position and orientation using a fiber optic gyroscope and the Unscented Kalman Filter (UKF), which estimates a probabilistic distribution using small range of numbers taken from specifically chosen test points. This approach assures better position and orientation accuracy in comparison with the Extended Kalman Filter (EKF) approach.

Motion planning and control

There are many aspects of the operation of a typical industrial manipulator or vehicle that must be planned and coordinated. Planning includes the determination of an optimum and safe no-collision path that the vehicles will have to follow, while ensuring high precision docking with conveyors or other equipment. Advanced planning operations include the positions of tools and material in specific locations. Until recently, vehicles modified their trajectories in order to enable coordinate motions and ensure obstacle avoidance using an offline approach. However, future research should focus on enabling the vehicle to modify its trajectory while operating. This implies highly intelligent control architectures and suitable sensor feedback.

Planning coordination using centralized computation methods are not suitable for AGVs and mobile robots used in the mining industry, wherein the environment is less structured and the tasks are not known in advance. The decentralized estimation schema, or distributed approach seems to be more appropriate in such locations. Because the paths that are planned in this environment are not fixed, special attention must be taken for high-accuracy docking maneuvers, in order to increase the flexibility and adaptability of robotic configuration modifications (Herrero et al., 2013). For manipulators, appropriate joint planning configurations are needed to fulfill certain coordination tasks. In order to operate the robotic manipulator with absolute precision even at higher speed, the control strategy has to be well defined. Robot dynamics, payload and, operating environment are the main challenges in designing the control system. The control design of a manipulator depends greatly upon the studied application scenario. Recent advances in manipulator control have been categorized into three sub-domains: *Intelligent Proportional–Integral–Derivative (PID) control, robust control* and *adaptive control*.

There is a continued interest in modifying a simple PID control to improve control performance and functionality (Blevins, 2012). Some of the possible ways to modify a PID control are presented by the study of Fei and Wu (2006), where they cascaded through multiple controllers. Advancements in PID control include the combination of PID control with modern control techniques and algorithms to achieve optimum performance, improvements on tuning methods (Foley et al., 2005; Nagaraj and Murugananth, 2010), and modifications with non-linear and adaptive control approaches (Iqbal et al., 2014).

Regarding the robust trajectory tracking techniques, Ullah et al. (2014) used Computed Torque Control (CTC) (Fei and Wu, 2006) algorithm in a 6 Degree of Freedom robotic arm with 5 revolute joints. This control technique cancels out possible nonlinear behaviors of the studied system and then uses linear modelling dynamics to accomplish the desired position and orientation. Literature has been reported in Piltan et al. (2012), combining Computed Torque Control with PD and PID. Nguyen-Tuong et al. (2008) demonstrated a comparison between Locally Weighted Projection Regression (LWPR) and Gaussian Process Regression (GPR).

Robotic arms for underground mining

Robots equipped with robotic arms can improve the performance of human workers in harsh working environments like underground mines. Lösch et al. (2018) showcased a robotic system that has a UR5 robotic arm and a 3-Finger Adaptive Robot Gripper from Robotiq with which the system can then install, rearrange and remove Smart Sensor Boxes (SSBs) of an Internet of Things (IoT) infrastructure. Robotics researchers also work together with mining experts to autonomize existing machines in the mining industry. For example, Bonchis et al. (2013) adapted a mechanical manipulator from a Palfinger truck crane for explosive charging tasks. They designed an end-effector that carries the laser rangefinder for detecting the location of the blast holes, and they used a number of video cameras and LED lights to support the automatic and manual host insertion process. To insert the tool into the blast hole, the manipulator is first controlled by a planning algorithm and then teleoperated by a human operator to refine the position and direction of the end-effector. To perform different tasks underground, the robotic manipulator can be very different from traditional robotic arms. To replace human coal miners in Korea, Huh et al. (2011), designed a tele-operated mining robot that has a boom, an arm and a bucket.

Hydraulic actuators can be direct drive for linear or rotary motions. Lu (2009) shows how a bucket wheel reclaimer can be converted into a robotic arm and can be controlled automatically. In his work, he first modelled three joints of a typical BWR, based on which the kinematics and dynamics are modelled. In the study of Peshkin and Colgate (1999), the authors conclude that Lagrangian dynamics models and Newton-Euler dynamics based models for hydraulic robotic manipulators, provide superior control performance and give solution to highly nonlinear behavior of energy inefficient hydraulic systems. An example of a mobile robotic manipulator is displayed in **Figure 2.5**. Based on the study of Grehl et al. (2017), the Julius robot consists of an articulated three-finger hand mounted on a robotic arm. The preliminary survey explores co-working scenarios, where Julius is deployed to assist the miner using its robotic and the three-finger gripper with demanding, precise or risky tasks. To achieve its goals, Julius carries wi-fi stations and uses its gripper to place them on the floor to extend the network range when the wi-fi signal becomes weak. Its arm is used in various applications, such as collecting water samples in abandoned areas, handling the mine ventilation system and investigating the underground area for loose rocks debris using its gripper's camera.

2.6 Human-Robot Interaction on Underground Mines

The term Human-Machine Interaction (HMI) is attributed to the low level of autonomy and complexity of interaction with industrial robots (Vaughan et al., 2012). The introduction of autonomous machines and robots on large scale mines is a new trend in the mining industry (Grehl et al., 2015; Thrybom et al., 2015). Robotic systems and mine automation applications have already been well developed in open mines (Rizos et al., 2011; Boulter and Hall, 2015; Dadhich et al., 2016; Lindmark and Servin, 2018), while in underground mines, robots are used primarily on well-developed infrastructures (Plotnikov et al., 2020), the majority of them including the development of automobile vehicles (Polotski and Hemami, 1997; Roberts et al., 2002). On a mine

Figure 2.5: An articulated three-finger gripper allows Julius to operate devices designed for human hands. The precision and endurance of the robotic gripper increase the measurement quality. Figure retrieved from Güth et al. (2018)

site, there is a large number of independent equipment and systems. Each has its own information and interface. These machines complement human capabilities and relieve them of arduous tasks, as well as reduce energy costs in remote locations while limiting safety issues.

It is becoming more common for human and robot co-workers to work on a dedicated workstation as collaborators, in order to accomplish tasks in industrial environments. An industrial robotic system may include one or several robots and one or several humans collaborating in conjunction to accomplish tasks. Moulières-Seban et al. (2017) asserts that the design of a robotic system involves a clear understanding of the possible humans, tasks, robots and system interactions.

This has led to the need for advanced human-robot communication that can combine cognitive skills, intelligence, flexibility and decision-making of humans (Modares et al., 2015; Djuric et al., 2016). The goal is to combine robotic strength, endurance and accuracy with human intelligence and flexibility (Krüger et al., 2009; Müller et al., 2016). Argall et al. (2011) proposed a method of teaching in which primitive components of motions are learned by a robot through teleoperation. This method can be used to help robots perform a complete task without the operator having to determine all aspects. Farry et al. (1996) respected the principles of the detailed myoelectric signal processing approaches in order to create a complex robot hand that reproduces the motions of the operator's hand in realtime. According to Pedersen et al. (2012), a mobile manipulator can use gestures to determine whether to pick up and where to place an object. This method requires the definition of gestures. These must be easily distinguishable by the sensors on the mobile robot, as well as communicable by humans. Other researchers have tried to improve human safety by creating robots that determine where and who can ask for help (Rosenthal and Veloso, 2021; Veloso et al., 2015). Sisbot et al. (2007) presented a solution for safeguarding the workforce near robot locations. The approach consisted of a path algorithm that computes the comfort and expectations of people that may be near the robot. This path-planning technique assures a safer distance between the robot and the workforce, and it positions the robot in a clear and wide field of view to prevent surprise appearances.

2.7 Safety Issues Related to Underground Industrial Robots

Safety and security issues related to industrial robots should always be addressed upon control development. Vasic and Billard (2013) identified a range of different threats to all humans surrounding robots. Guiochet (2016) studied the catastrophic consequences of a failure or extreme environmental conditions and how life threatening those situations can be. According to Pedrocchi et al. (2013), safety tactics can be broken down into the following:

(i) Intrinsic safety.

(ii) Preventative collision techniques (*pre-collision*).

(iii) Techniques activated when a collusion occurs (*post-collisions*).

The authors in Colgate et al. (2008) study addressed that it is almost impossible for heavy conventional industrial robots to behave in a gentle and safe manner when realistic conditions are taken in consideration. The following paragraphs are assigned to the various attempts of authors to design an intrinsically safe robot based on the aforementioned conditions.

As specified by Bicchi et al. (2008), the first step in increasing safety performances, is to introduce compliance at the level of mechanical design. Other researchers have proposed increasing the robot's sensorial apparatus in order to mitigate the risk of an accident (Colgate et al., 2008).

Some researchers have proposed increasing the robot's sensorial apparatus to mitigate the risk of accident (Zhou, 1995; Cirillo et al., 2013). The first lightweight arm named whole-arm manipulator (WAM) was proposed in Salisbury et al. (1988). Recent examples of human-safe robots are the ABB YuMi (ABB, 2015), the Rethink Robotics Baxter and Sawyer (Robots, 2015; Robotics, 2015) and the KUKA LBR (KUKA, 2016). Note, however, that safety in human-robot interaction extends beyond physical contact. In fact, previous work (Butler and Agah, 2001; Mumm and Mutlu, 2011; Lasota et al., 2017) has shown that a robot's appearance, embodiment, gaze, speech, and posture can have negative psychological effects. It is necessary to achieve higher safety standards by preventing unexpected collisions between humans and robots. Those collisions must be determined and avoided before any injury occurs. Current practice in industrial robots is the use of proprioceptive/exteroceptive robot sensors to detect the presence of moving obstacles or humans and stop task execution to avoid contact. Based on real-time detection techniques and reactive planning algorithms, researchers have allowed a higher degree of coexistence and interactions between humans and robots (Djuric et al., 2016; Ferrara et al., 2019; Safeea et al., 2019).

2.8 Tele-operation and Shared Autonomy

The human-robot communication interface is crucial for safe deployment of robots in underground mining because of its environmental complexity and variety. Ideally, humans should be able to monitor and interrupt the working progress of robots remotely in a safe place. In Huh et al. (2011), a tele-operation system is implemented via remote-control station where humans can control the robot with joysticks. It is also important to inform humans the status of the robot and the working progress in a human-friendly way. The remote-control station has two monitors that show the robot, as well as obstacles in the work area. To enable a equipment sharing scenario, (Wilkinson, 2004) suggests a new, cooperative approach to teleoperation in mining environments.

Wilkinson (2004) also proposes an interactive telemining simulator to help quantify the interaction between operators in a dual operator configuration. In direct teleoperation, users provide inputs that are then directly converted to robot actions. However, direct tele-operation is often tedious and time-consuming, especially for robotic arms that have various degrees of freedom. Previous approaches on shared autonomy have combined teleoperation with autonomous assistance, where the system predicts the goal of the operator and then assists the operator in that goal (Abbink and Mulder, 2009; Passenberg et al., 2011; Rakita et al., 2019). Haptic interfaces have been particularly effective in adapting the automation to allow the user to regulate the control authority delegated to the system (Abbink et al., 2012). Researchers have regulated the stiffness of the control system so that the user can opt to delegate control or initiate taking back control (Javdani et al., 2018; Nikolaidis et al., 2017).

2.9 Conclusions

An integral part of the study was reflected in the pages of this chapter. With reference to the aforementioned literature, mining environments are difficult to alter to suit the simple and easy application of automated systems. So far, there is little familiarity with robotics implementation potential in mines. Acceptance by mine owners and miners, integration of robotic selection, design and application in mining operations, robotic equipment reliability and productivity, prevention of mining fatalities and injuries without changing the mining methods, and development of optimum fail-safe engineering controls are all factors that need to be considered and addressed coincidentally. Few more issues and challenges related to industrial robotic systems are briefly outlined in the following enumeration:

(i) develop robust detection of human movement to build good predictive models,

(ii) ensure robust detection of contact between robots and workforce in multiple points,

(iii) develop fast responsive controllers for real-time local trajectory replanning for complex underground mining environment,

(iv) ensure satisfactory real-time constraints, and

(v) develop a reliable system structure for fault tolerance, by including three main principles: *error detection*, *error diagnosis* and *recovery*.

The development and utilization of autonomous vehicles have obtained great attention in many engineering and scientific applications. Such applications include, but are not limited to, underground/surface mining, intelligent transportation, agriculture, marine and extraterrestrial environment exploration, disaster reconnaissance, and rescue. The necessity of autonomous heavy machines lies in the insufficiency of humans to carry out desired tasks due to inaccessibility (e.g., deep water excavation, planetary exploration, confined areas) or the prevalence of hazardous conditions (e.g., nuclear radiation, toxic gases). In terms of mining, mining automation is used for monotonous jobs. The necessity of precision and speed that a human cannot perform is essential for such tasks. The benefit is that those jobs can now be executed faster and more precisely by using autonomous mining equipment, while at the same time, the risk for the operators is reduced as they are removed from active and potentially hazardous areas.

Chapter 3 Research Hypothesis and Methodology

3.1 Introduction

Over the last decades, the utilization of autonomous heavy mining equipment has resulted in the mining industry increasing the health and safety of mine personnel by lessening their exposure to adverse conditions (e.g., hazardous dust particles generated during underground mining activities). Automation strives to remove the operators from unsafe conditions present in active mining sites and place operators in a more convenient and safer settings at a distance from the active mining face. Each section of this chapter defines the purpose of the discussed automation system and specifically demonstrates the feasibility of incorporating the autonomous roof-bolter in the underground coal mining cycle. Parameters to be studied are:

(i) Network communication between roof-bolter and robotic arm,

(ii) mechanism and design guidelines for autonomous roof-bolting cycle,

(iii) drill bolt size,

(iv) drill bolt length, and

(v) drill bolt spacing/coupling.

The automation objective is explained in the context of the respective mining system. Thus, the control problem is related to specific issues of safety or protection of the surrounding working environment and, in general, optimal use of the particular system.

3.2 Background

The robotic arm installation project requires re-imagining the bolt installation procedure on the dexterity of the human operator. Locating the installation assembly will rely on the operator or an automated machine-positioning system. The basis of the project is to use a 6-axis anthropomorphic robot in place of a human to handle the drill steels, bolts and other consumables. This robotic assembly will carry out the entire sequencing of the roof-bolting. The hydraulic system will be synchronized with the robot's operations. A human operator will be required to approve major operations, while the operator also maintains the ability to operate the robot and the hydraulic system.

Overview of the roof-bolting cycle

Roof-bolters operate a bolting rig that uses pneumatic or hydraulic power to install roof support bolts in underground mines, preventing cave-ins. Soon after coal is extracted, the roof's rock strata must be promptly secured. Drill bits, extension steels, resin roof bolts, and cable bolts are used to safely support the roof. Dowels, shotcrete, mesh and steel sets can be generally used for rock support. The positioning of the holes follows specific safety rules, and; then, the bolt is installed. The end of the bolt is tightened using a turnbuckle tool. Each bolt is tested for the specified tension using a torque wrench. The type of support installed in a specific underground mine relies upon the ground conditions, such as the extend of fractured or jointed rocks encountered near the excavation. Rock support installation is carried out as an integral part of the excavation cycle to secure the roof rock mass self-support. This process is crucial to the operator's safety and the ventilation of the mine. After installation, the roof-bolter needs to be re-positioned and inserting the next bolt continues.

Underground mining involves repetitive processes in confined and hostile environments. Roof-bolter operators are prone to exposure to hazardous conditions, due to their proximity to the unsupported roof as well as dust and noise exposure. This confined work environment forces the operator into uncomfortable postures for tasks that require quick reactions to avoid contact with moving machine components. After hand tools, the roof-bolter machine is responsible for the second-highest number of nonfatal lost-time injuries, where the average injury incurs several months away from work. Physically demanding job over extended periods in unfavorable environments also increase the probability of unsafe actions, leading to accidents or near misses.

For instance, the operator needs to maintain an arm's reach distance of 20 to 30 inches from the moving boom arm since their primary job is to handle the hydraulic controls and place the drill steels and bolts near the drill head. Other factors are, but not limited to, wet or muddy conditions, uneven floor, and the required mining gear (Ducarme et al., 2010). This research aims to develop automated processes within the roof-bolting process with the ultimate goal of removing humans from hazardous environments. An overhead view of the robotic arm alongside a simulated roof-bolter is shown in **Figure 3.1**.

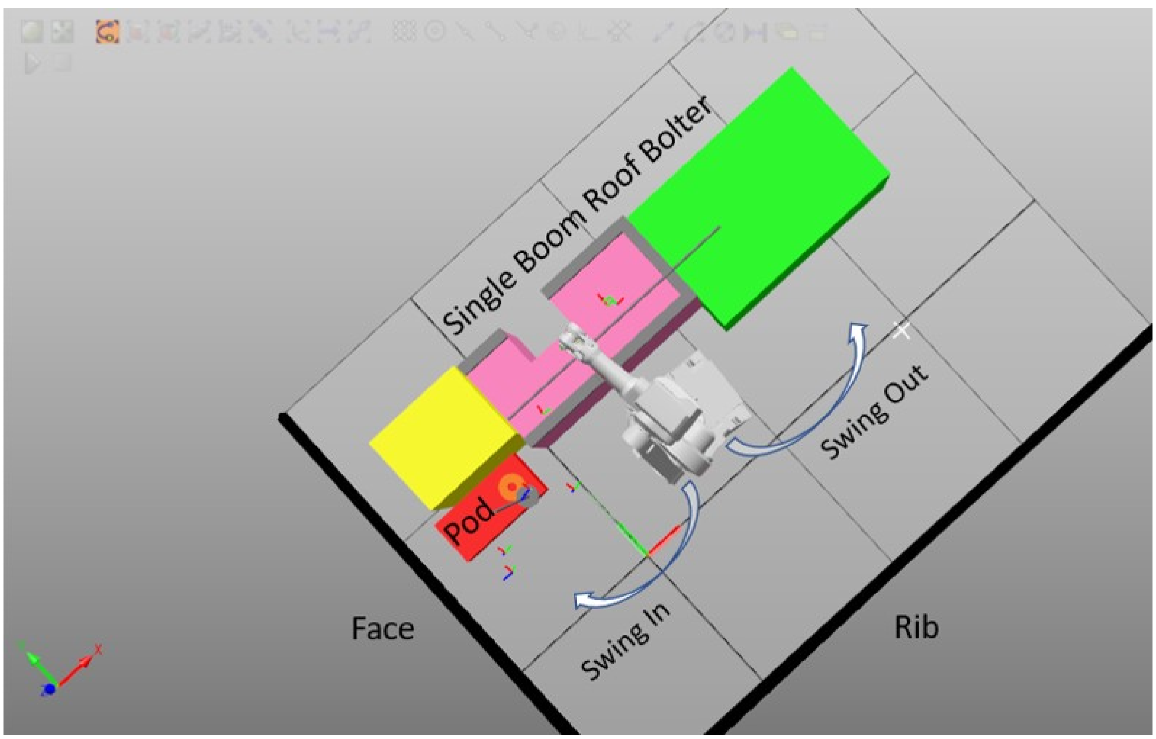


Figure 3.1: Overhead view of a robotic arm alongside a simulated roof-bolter

The robotic arm movements will involve the following actions:

(i) Insert the drill steel in the chuck,

(ii) add extension steels (if required),

(iii) add resin,

(iv) spin to mix resin/torque the installed bolt, and

(v) remove the steel.

This bolting sequence repeats until the unsupported area of the roof is secured and the requirements of the roof control plan are met. Then the remote operator moves the machine to a new location and begins the process again. Roof-bolting is a fairly structured and repetitive process.

Overview of the laboratory roof-bolter set up

Carlson's Software three-dimensional (3-D) scanning laser system is an underground laser cavity monitoring system that was used to digitize the roof-bolter module. The purpose was to have a machine model that allows the research team at UKY to have accurate 3D access to the machine for their modeling efforts. The machine was scanned on a medium-high detail density, and the point cloud was stitched and simplified before being delivered back to the research team from Carlson Software, shown in **Figure 3.2**.

3.3 Limitations

A method for installing roof bolts in a mine passage using an autonomous roof-bolter poses several challenges. The established work cycle is often altered due to external influences, such as changes in geology (i.e., mine layout, work in confined space, interruption by co-workers or interaction between humans and mining equipment), machine malfunctions (i.e., wireless technologies with severe line-of-sight limitations), and supply problems (i.e., reload roof-bolter). A characteristic feature of the coal mine that must be considered for the design of the methodology of the autonomous roof-bolter during the development phase is the blind crossing intersections or entries along a planned path when personnel is present. For this reason, proper regulations of human-machine interaction must be introduced.

A protocol for human-machine interaction will determine how the operating personnel and the other mining engineers should cooperate and communicate with the autonomous roof-bolter. In addition, the successful incorporation of the autonomous roof-bolter in underground coal mines depends upon the acceptance by the mining

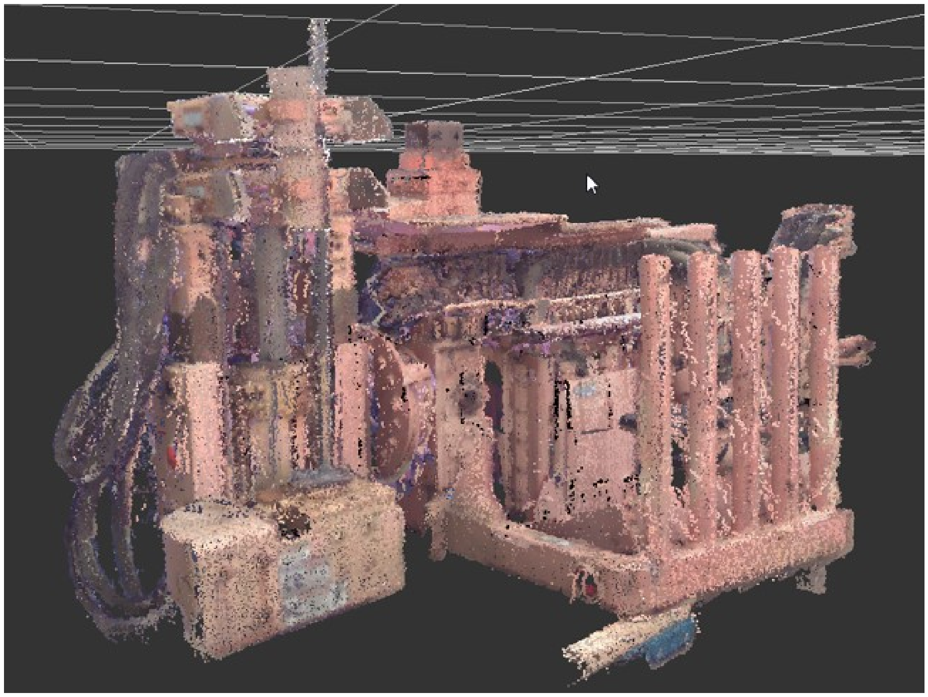


Figure 3.2: Laser scanner point cloud, shown in Autodesk ReCap

operators. The employees involved must understand that the goal of the autonomous roof-bolter is to:

(i) Assist workers in hazardous work conditions that jeopardize the miner's health, such as excessive heat, dust, toxic smoke, or soluble gases like hydrogen sulfide (H2S), and

(ii) provide an opportunity to increase health and safety.

In comparison with the surface autonomous mining technologies, the underground mine environment limits the functionality of sensors. And while wireless technologies can be implemented, they require additional appropriate infrastructure. Finally, a fundamental mechanical concern that needs to be addressed is the robotic arm's electrical-powered trailing cable through the robot's controller. This makes the maneuverability of the roof-bolter a challenging process, because the power center should be relocated in relation to the roof-bolter's position, while at the same time, limits the distance that the roof-bolter can move through a specific mine passage.

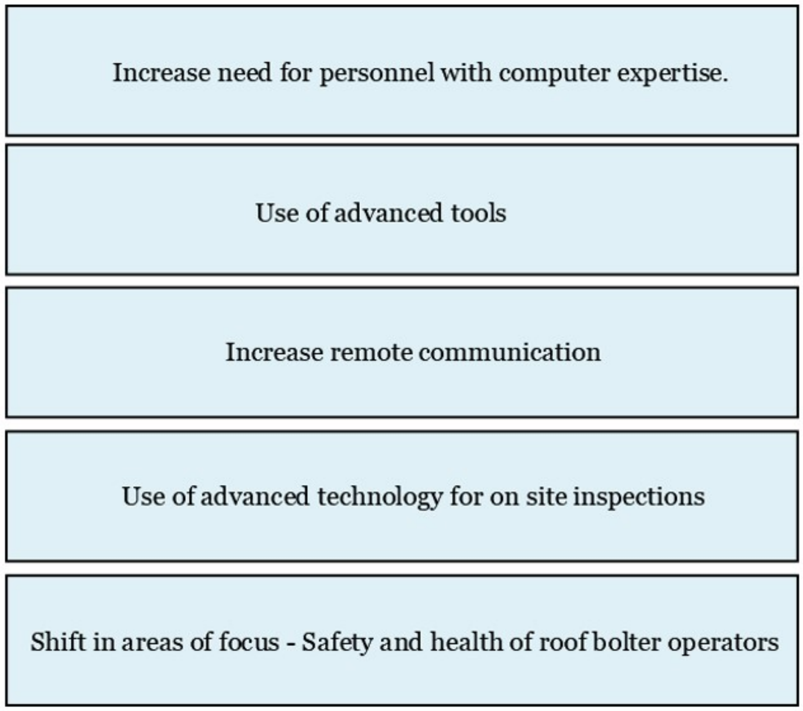


Figure 3.3: Most significant changes to impact the roof-bolting cycle in the following years

3.4 Association Amid Communications and Safety

Corporations have placed the most significant emphasis on the safety of underground coal mining operations. More and more frequently, robotic autonomy has assisted in operating in those inoperable environments for humans. Secure communication is significantly crucial for the success of autonomous roof-bolting systems. A secure communication system will allow the command center to guide the roof-bolter into the desired position and manage the drilling cycle to track the whole mining operation. Therefore, mining is in no way different than any other sector of technology; with the introduction of such technological advancements in communications, operations are prone to suffer from the vulnerabilities. In mining, the autonomous roof-bolter must maintain continuous communication with the central control room, and communication failure will ultimately mean that the whole operation will stop, even when the control room is focused on a single piece of equipment. Indeed, a stable wire and/or wireless network infrastructure is critical to autonomous roof-bolter operations.

3.5 Laboratory Analysis of Autonomous Roof-Bolter

Build and test the robot assembly

The robotic arm is designed to carry out roof-bolting with minimal human intervention. This is built from individual components of the module, which are also tested for their motion under different constraints. A human-computer interface is built to enable the interaction of the operators with the machine. The operators will constantly approve all actions of the hydraulic machinery and will have the authority to overrule any actions that might be deemed unsafe.

Build an analog of bolt module

The Department of Mining Engineering at the University of Kentucky has a laboratory space equipped with electrical power, compressed air, vacuum, heavy lifting equipment, 3D-printers, and other relevant facilities to aid in research projects, including building a prototype of the bolter module. This prototype can execute the motions of a production bolt module without heavy-duty work, like actual drilling of the rock mass. The purpose is to demonstrate the automation, not the cutting and affixing. The Department also has access to the College of Engineering machine shop manned by personnel experts in computer numerical control (CNC) and water jet cutting. A confined space to mimic the mining conditions underground has been designated in the Department of Mining Engineering for building the bolt module envelope. This space is also appropriate to test the bolting procedure on the immediate ceiling. The bolt module runs drill steel into these holes, places resin cartridges (not real setting resin), and runs bolts into these holes. The Department also has access to an underground research facility at a limestone mine operating nearby, if underground work is necessary. The specific details of mechanical systems of the roof-bolter which could be modified to suit the automation needs is studied. The researchers specifically plan to design mechanisms to:

(i) Replace the carousel with a bolt pin that can pick the drill steel and place with the arm,

(ii) Enable the robot to pick and stack the resin cartridges in the same manner, and

(iii) Enable grabbing the drill steels on the fly without having them to be stacked together, minimizing the force required to decouple.

A Programmable Logic Controller (PLC) was developed to monitor drilling operations. A Drill Control Unit (DCU) was also set up to automate the drilling and bolting cycle. The display and control can be activated through a rugged touch screen panel and the bolter module can be operated with a joystick. **Figure 3.4** and **Figure 3.5** show the CAN Bus interface that is integrated directly in the valve section for connection to the master control unit and for controlling the roof-bolter's hydraulic system. The control cabinet, shown in **Figure 3.6**, consists of the following units. In the first DIN rail, starting from left to right there is a IQAN-XA2 module, a costumer connections and a power supply. In the second DIN rail, starting from left to right, are the signal wires, the AnyBus Communicator - EtherNet/IP, the expansion block and the power protection.

Figure 3.4: CAN Bus connected and integrated into the hydraulic system

Figure 3.5: Control system installation process

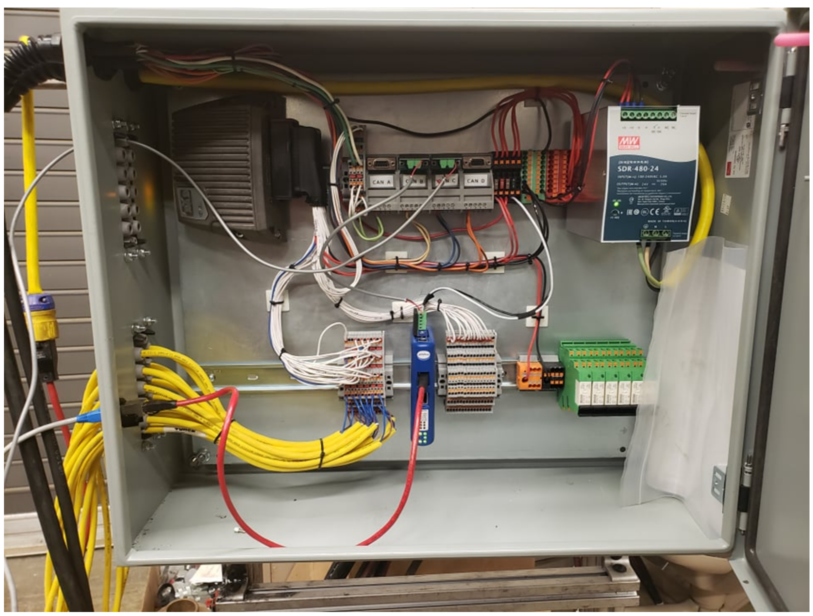


Figure 3.6: Detailed control cabinet

Development and testing of motion patterns

Individual components of the robot model are tested. This includes testing the robot model with all the assembled components. The assigned laboratory space, where the bolt module will be built, also allows testing multiple trajectories of the robotic assembly under confined conditions. Multiple obstructions of different sizes, shapes and reflective properties are added to space and customized trajectories using defined waypoints. These obstructions are used to develop trajectories avoiding slip, trip and fall hazards, and they finally mimic underground mining conditions with uneven surfaces, inadequate lighting and power cables running on the floor. The trajectories are programmed into an appropriate computer simulation software (e.g., ABB RobotStudio). A high-level programming language called RAPID is used to control the robotic arm. Suitable corrections using optimization techniques are built into the algorithm to account for deviations encountered in real-life mining conditions. The robotic model is scheduled to be tested in the nearby underground limestone quarry in Georgetown, KY.

An experiment environment was developed in ABB RobotStudio, focusing on validating the following aspects: (1) robot payload; and (2) maximum linear speed of the tool. It was found that the current setup should be able to fulfill the requirements induced in the roof-bolting task, and the robot model IRB 1600 with 10 kg payload capacity and 1.45 m reach was selected (**Figure 3.7**).

The simulated roof-bolting scenario is constructed based on the real roof-bolter. The dimensions of the model are based on measurements from the UKY lab, and the operations are based on information from the visit with RRLA. The research team validated that, with a 10 kg payload capacity, the robot is able to successfully manipulate the common drills used for roof-bolting. Several payloads were tested to determine the maximum payload the robot can move under different grasping scenarios (**Table 3.1**). The results show that it is better to constrain the grasping position near the middle point of the drill than try to use a larger robot. Furthermore, the research team validated the maximum linear speed of the tool the robot can reach. The linear velocity of the extended arm was tested since it is critical for the robot to perform this dangerous task as fast as possible. The linear speed plot of the tool is presented in **Figure 3.8**. It was also found that the maximum linear speed the robot can reach is 3091.32 mm/s which was considered sufficient for the task. These test results indicate that the current simulated setup does not exceed the robot's capabilities.

The robot-commanding interface is comprised of two parts: (1) socket server/-client; and (2) modular robot commands. The socket server/client sends commands

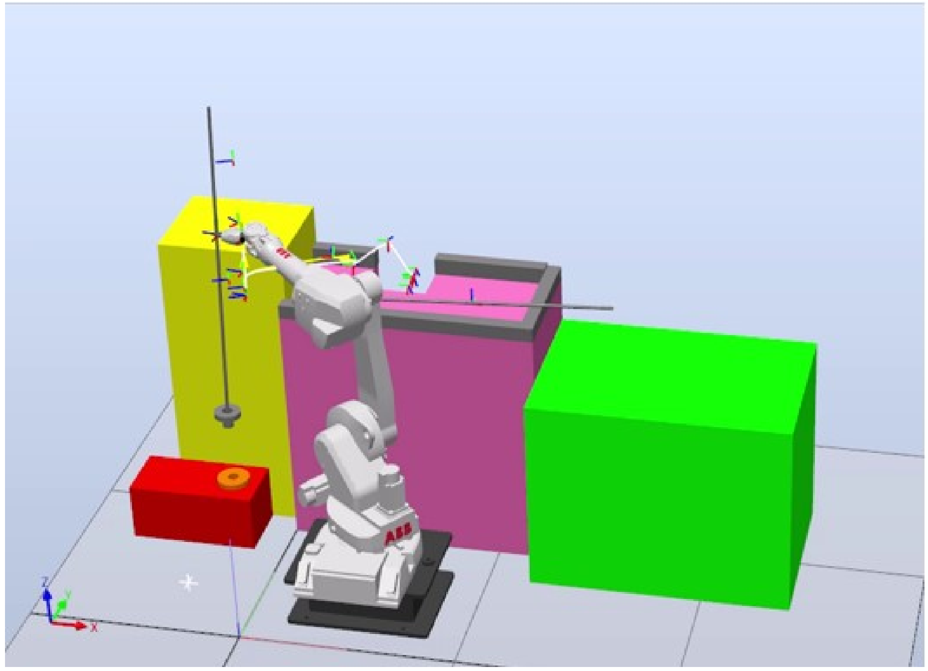


Figure 3.7: Simulated roof botlting environment

from one computer to another computer. In contrast, the modular robot commands send different robot commands in a much more flexible manner. The interface is programmed in C#. The interface consists of three modules: a server, a client, and a module that implements the RobotStudio API, which is connected directly to either the virtual robot in the simulation environment, or the actual ABB robot in the real world.

(i) RobotStudio API module: The RobotStudio API module interfaces directly with the RobotStudio controller; it runs on the computer that is physically connected to the robotic arm. The interface sends commands of the form "MoveToStart"; when the RobotStudio controller receives the command, it executes a function of the same name. The function is written in the RobotStudio RAPID code, and it includes low-level commands. For instance, the "MoveToStart" motion, includes the coordinates of the start position and velocity and acceleration limits that the robot should follow throughout its motion. The controller then computes a sequence of torque commands, sent to the robotic manipulator.

(ii) Server: The server connects with the RobotStudio API module, and it listens continuously for connections with a client through a static IP address. The server also interfaces all the functions implemented in the RobotStudio API module. This allows an external client to connect to the server and send commands to the robot.

(iii) Client: The client contains a GUI interface. It allows the user to see the available functions and call the desired function by pressing a button. The client will then send the command to the server, which in turn communicates it to the client.

Table 3.1: The max load the robot can move for different grasping positions

Grasping Position	Max Load (kg)
1/2	24
2/5	7.2
1/3	4.2

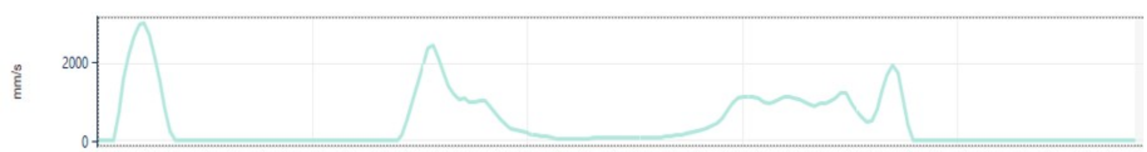


Figure 3.8: Linear speed plot of the tool for one task rollout

Development of HCI for machine operator

In this project, the development of a human-computer interface (HCI) has been the primary goal. The geometry, position, and orientation of the drill steel, resin cartridges and obstacles are displayed to the operator. An interface that requires the operator to approve every task before being executed by the robot has been developed. Provisions are made to let the operator override the computer programs in case of emergency or unexpected actions.

A robust failure detection protocol is built into all the programs. The protocol continuously checks the vital parameters of robot operations. The operator is notified via alarm systems should any abnormalities arise when compared against the expected position and orientation of the robot. Virtual sensors are used in the computer simulation environment to simulate error/ failure events. The operator is provided with options to rectify the errors and reset/ re-calibrate the machine. For more intuitive and user-friendly human-robot interaction, a human-robot interface was designed and developed, through which the user can send commands to the robot and monitor the robot status in real-time, for both computer environments and flex pendant devices. The human-robot interface for computer environments is targeted at providing an easy-to-use interface for users to command the robot on desktop computers, smartphones or tablets, presented in **Figure 3.9**. It has three components: GUI client, server, and video streaming server. The Qt cross-platform library is used to develop the graphical interface. There are three components of the graphical interface: logging area, command sender and real-time robot video streaming player. The logging area is where the messages sent from the robot, e.g., the last command is finished, are printed. The command sender has different buttons corresponding to different robot motion modules. The real-time robot video streaming player is where the user can monitor the robot's movement in real-time.

The video streaming server is a program that can efficiently decode and transmit images. It communicates with the client through the WebSocket protocol. The server connects with the RobotStudio API module, which is connected directly with the robot, and it listens continuously for connections with a client through a static IP address. The server also interfaces all the functions implemented in the RobotStudio API module. This allows an external client to connect to the server and send commands to the robot.

The FlexPendant is a handheld operator unit used to perform many of the tasks involved when operating a robot system. In this project, the FlexPendant is used when the human operator is required to work closely with the robotic arm in various roof-bolting activities, or for maintenance. The human-robot interface for the FlexPendant is developed using the ABB ScreenMaker software. The interface consists of different buttons corresponding to different motion modules.

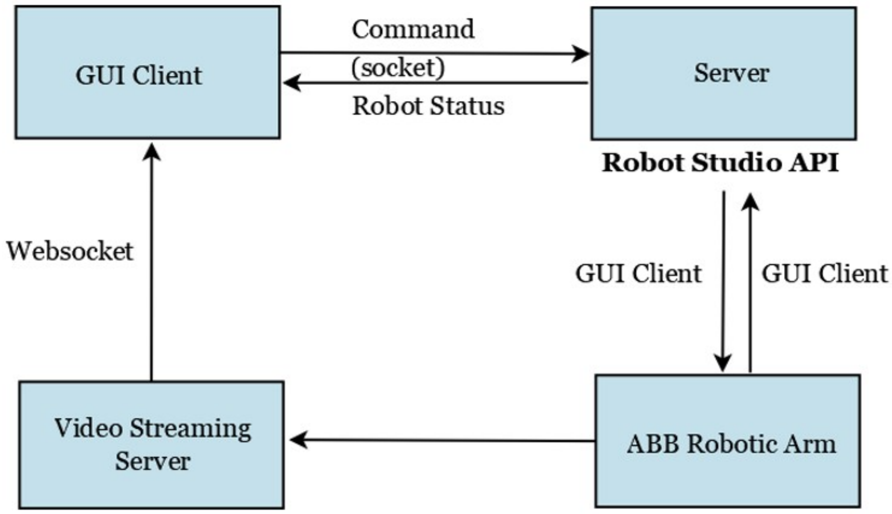


Figure 3.9: Human-robot interface for computer environments

Integration of individual actions-HMI

The motion of individual components is integrated into the robotic assembly and the software is updated accordingly. The trajectories of the robotic arm, including the angle, velocities and acceleration of all joints have been studied. Attention is directed to the coupling of the components since some of them are required to move together (parallel events), while some operate once a preceding motion has been executed (series events). Suitable buffer times were built into the computer software for a smooth transition between motions of individual components. The computer software was modified to realize the desired motion.

Time studies of the individual mechanisms were carried out, followed by time studies of a complete cycle of roof-bolting. The researchers examined the mechanism iteratively to minimize the time required for safe operation, towards reducing the overall cycle time of the operations. The human-computer interface was fully integrated and functional with the physical model of the robot at the end of this stage.

A human-machine interface has been integrated to enable a manual approval of the tasks and override the system in the event of unpredicted or unsafe activities. It is necessary to mention that an online in-situ drill monitoring system is needed to evaluate the quality of the bolting process and provide information on rib and roof integrity. The initial focus was on creating the analog of the bolt module. Analytically, building an analog bolt module involves the following stages:

(i) Roof Bolt Ejection – the first stage of the installation process involves the ejection of a roof bolt from the storage magazine. A series of robotic movements that operate in turn assist the ejection process. The result is that a roof bolt is dropped into the jaws of the bolt transverse device (chuck).

(ii) Roof Bolt Vertical Placement – once at the pod, a small hydraulic jack and clamp arrangement rotates the roof bolt vertically.

(iii) Roof-Bolter Loading – the roof-bolter extends the drill motor up, so the roof bolt sits in the chuck. Once the roof bolt is seated, the carousel releases the grippers on the roof bolt so the roof-bolter can assume the next roof bolt installation position.

(iv) Installation Position – the loaded roof-bolter assumes the next installation position with assistance from the strata profiling system, used to survey the strata profile for optimum bolt placement in the support pattern being installed. Specifically:

   a) The roof bolt plate magazine located on the side of the bolting slide frame ejects a plate on top of the head plate;

   b) The head plate of the bolter extends up to the roofline, with the roof bolt plate to secure the bolter to the roof strata;

   c) Drill rotation and drill feed commence and operate under monitored rates to ensure optimum drill performance;

   d) Once the self-drilling roof bolt has been drilled, a set amount of chemical resin is injected;

e) The drill head retracts down the bolt slider, and the head plate retracts of the roofline.

(v) Reload Roof-Bolter – the autonomous robotic arm returns to the original position, where the bolter docks in position to load the next bolt.

3.6 Conclusions

The study shows that fully autonomous systems and semi-autonomous features can be applied in a broader range of repetitive roof-bolting tasks. Tracking systems and collision avoidance solutions need to be taken into consideration before employing the operatorless roof-bolting equipment. Although, based on the findings of this chapter, a proposed system that will allow each party on a job site to work independently, without the disturbance of co-workers, is the optimal solution for enhancing miner safety and increasing the productivity of site operation. That is, the robot movements will not be halted upon detection of a miner's motion. Instead, the miners will communicate their intention to the roof-bolter's system without completely stopping the drilling operation. On the other hand, the autonomous bolter will have to safeguard the human operators working on the face. With the introduction of automated functions and machines, soon, there will be a need to re-educate the mining workforce to enable a more efficient and sophisticated collaboration with the autonomous bolting system, allowing for safer operation.

Chapter 4 Concepts for the Development of the Autonomous Roof-Bolter

4.1 Introduction

A detailed study of human motion is carried out using computer software. The study is based on the operator's movement relative to the motion of a roof-bolting machine boom arm. Results are used to guide the development of a robust remote calibration diagnostics and self-monitoring system, to integrate a human-machine interface that enables a manual approval of the tasks, and to override the system in the event of unpredicted or unsafe actions. Although this project aims to provide a better working environment for operators, productivity and the value of immediate roof observations should not be discounted.

4.2 Description of the Autonomous Process

The construction of a robust autonomous roof-bolter, able to carry out required tasks is based on an appropriate architecture that will enable it to make decisions similar to those made by humans. The autonomous roof-bolter must be capable of sufficient robotic spatial perception, robust remote calibration diagnostics, and self-monitoring capabilities. Overall, the autonomous roof-bolter must successfully perform the following functions: drill steel positioning, drilling, bolt orientation, and placement, resin placement, and bolt securing.

The foundation of an autonomous roof-bolter is the control module. A Programmable Logic Controller is developed to monitor drilling operations. A Drill Control Unit is also set up to automate the drilling and bolting cycle for improved safety and productivity. The systems are tested in the Rock Mechanics laboratory at the Mining Engineering Department, University of Kentucky. The display and control can be activated through a rugged touch screen panel. A CAN Bus system interface is integrated directly in the valve section to connect to the master control unit and control the roof-bolter's hydraulic system. The CAN Bus system has the bandwidth to cope with real-time control and data collection, while significantly improving flexibility. A joystick controls the drilling operations of the roof-bolter. Sensors monitored by this centralized system used for controlling or monitoring roof-bolting parameters (temperature, pressure, height of roof) by using CAN interface, are connected to the expansion block. This module continuously operates and is responsible for monitoring the control module, assuring that is working correctly and that the robotic arm does not deviate from the desired path.

The determination of contact incidents for each component resulted in the following possible occurrences:

(i) In the case of a collision between the machine and the operator, the user can immediately stop the operation and release the operator.

(ii) A complete analysis of the interaction allowed for analysis of situations where no contacts or avoid incidents occurred.

This analysis provides information that helps make recommendations to reduce the likelihood that roof-bolter operators are injured from contact with the robotic arm and roof-bolter boom arm.

4.3 Controller Setup

iQAN

Parker Hannifin have developed a line of control system products under the name IQAN, which are used for controlling the hydraulic systems in mobile machines. The IQAN system allows the user to monitor different IQAN-units that are connected together through a CAN-network. IQAN is usually used together with Parker Hannifin's valves and other control systems in order to monitor and control the behavior of the machine on which it is operating. It has the possibility to create its own control scheme, in a similar way with blocks as in Simulink; however, this is not used for this project since it will not allow custom algorithms. The main reason for using IQAN is the easy access communication protocol of CAN, which will be discussed more thoroughly in the next subsection.

CAN Communication protocol

To send the generated code to the ECU, a Controller Area Network protocol is used to transmit and receive data. The generated Simulink code can be uploaded through a USB CAN adapter and then be used by the ECU. The CAN protocol is a standard for industrial communications, and it has its benefits of low cost, priority messages, error capabilities and a lightweight network. The CAN protocol has primarily been used in the automotive industry, but it is now very popular in hydraulic systems due to its convenient properties. The CAN terminology can be explained as the CAN device sending data across the CAN in packets called frames, referred to as messages. In the CAN frame, each signal is contains 8 bits of data and each frame can contain up to 64 individual signals and 8 bytes of data for the entire frame. For our system, the main signals communicated by the CAN protocol are the measured pressure in service ports A and B and the command signal from the operator. The monitored signals can be chosen differently, depending on what the user is interested in, which is calculated via the controller.

For this thesis, the main signals that can tell us how well the adaptive control acts are the estimated frequency, estimated damping, the control signal, and how well the effective load pressure is damped. Besides the signals used to monitor the controller's performance, the communication also allows the user to send parameters to the controller for easy online tuning. This will be very convenient when tuning the controller online. Since the CAN protocol is done in binary, each message received will be encoded into a "real world" value. This is done by a module through Parker Hannifin's IQAN system, which supports CAN.

EtherNet/IP protocol

EtherNet/IP (EtherNet Industrial Protocol) - is a communication link connecting industrial devices.The EtherNet/IP is managed by ODVA (Open DeviceNet Vendors Association). It is a well-established industrial ethernet communication system with good real-time capabilities. EtherNet/IP extends commercial off-the-shelf ethernet to the CIP (Common Industrial Protocol) — the same upper-layer protocol and object model found in DeviceNet and ControlNet. CIP allows EtherNet/IP and DeviceNet system integrators and users to apply the same objects and profiles for plug-and-play interoperability among devices from multiple vendors and in multiple sub-nets. Combined, DeviceNet, ControlNet and EtherNet/IP promote transparency from sensors to the enterprise software. The configuration process is based on EDS files (Electronic Data Sheet) which are required for each EtherNet/IP device. EDS files are provided by the device manufacturers and contain electronic descriptions of all relevant communication parameters and objects of the EtherNet/IP device.

Component description

The master controller of the system is a Parker MD4 with an X7 expansion module running the iQAN interface, which includes a touchscreen and joystick. The iQAN interface communicates to the programming panel and the ABB and PLC controller through the AnyBus CAN to Ethernet/IP interface. A system block diagram is shown in **Figure 4.1**.

This design will allow a typical automobile class PLC to run the system, and therefore, it can immediately be placed on a vehicle. It also allows for sensors and other input devices to be placed where it's convenient. For instance, a sensor that is on the CAN bus can communicate values to the robot controller and the value be ignored completely by the PLC. Values that need to be passed between the systems are mapped by the Anybus.This project is the integration of several technologies and the communication between the devices is critical. However, during development, several testing and prototyping communication methods have been developed.

C# scripts (.NET framework) have been developed that use the RobotStudio API to control the robot directly. Other C# scripts have been developed to use the Kvaser CAN interface (a USB to CAN connection) to communicate directly with the PLC. The scripts can bypass the Anybus interface, and this allows the testing and development to move forward before the final map between the two interfaces is developed. Using CAN bus as the primary communication interface makes the communication network more accessible to sensors and other devices. Industrial ethernet protocols such as EtherNet/IP have a suite of sensors available, but the sensors tend to be for specialized purposes and are expensive. CAN bus interfaces are available and common because of their use on vehicles, including in mining and agricultural applications.

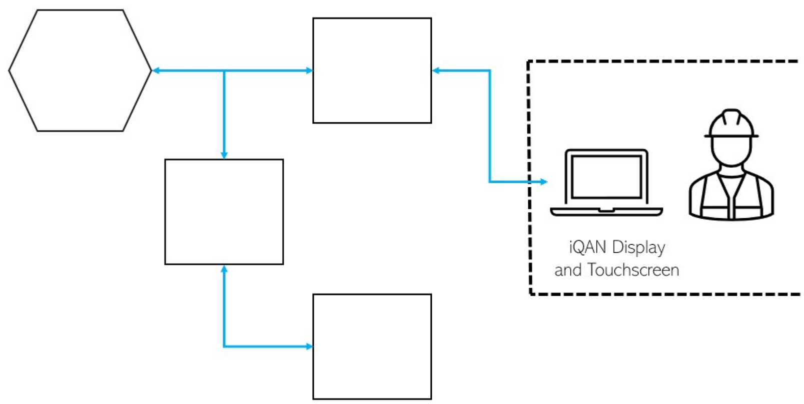


Figure 4.1: Block diagram and communication methods

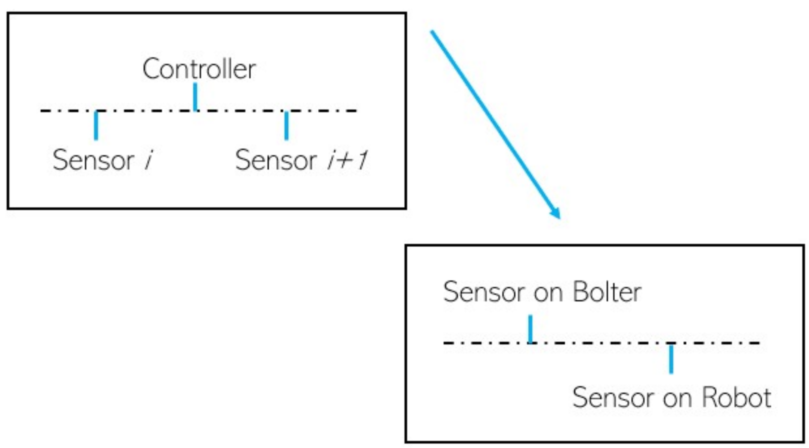


Figure 4.2: PLC and ABB mounting options

Figure 4.2 shows two different mounting options for sensors that may need to be included in the control of the system. Because of the communication architecture sensors can be placed where they will be the most convenient. If they report their values easily on CAN bus , as a bus-enabled sensor, but need to be consumed by the robot, the values can be translated into EtherNet/IP signals that the robot controller can understand. Similarly, if the sensor would easily be placed on the arm, as a distributed control, and uses the digital or analog signaling, it can be converted into a CAN packet and communicated on the CAN bus with little delay.

4.4 3D Parts

After meeting with J.H. Fletcher, the research team decided to change the drill size to one inch, while the machine was designed for a 1-1/2 inch drill. This requires multiple modifications to the machine that are also an opportunity to add functionality and sensors. Integration of the robot and the hydraulics requires a lot of fixtures and tooling. Design flexibility, time savings, and the ability to print remotely and on-demand were the main reasons for using the 3D technology. Also, the same models used to 3D print the parts can be used in the UKY Innovation Center to machine the parts or can be used by a local machinist to manufacture the parts. An example part that has a limited lifetime use is the chuck wrench, shown in **Figure 4.3**.

The part pictured is the first iteration; it fits in the chuck and was designed to engage the drill steel while spinning. As discussed below, the robot will put the drill steel in the clamp and the chuck must engage the steel. The angle of the opening on this wrench works very well for engaging the steel; however, this part is currently being redesigned. This part must also allow room for the coupling nut and be open. Eventually, this part must also engage with the resin injection system, which may require another redesign.

The drill clamps and guides, **Figure 4.4**, are parts that also needed to be re-designed for the smaller drill diameter. These parts will probably remain 3D-printed because of the pliability of the plastic. The drill guides will be much quieter for our purposes made from plastic; however, with a production machine, plastic may wear too quickly with the full speed of the head. The design for the clamps was originally modified specifically to grab the smaller diameter bolt and drill steel. With this design, adding a sensor to detect a successful clamp is possible. That modification may be necessary as the project continues.

The robot shipped from ABB with a simple end-of-arm tool designed for stacking

Figure 4.3: 3D-printed chuck wrench

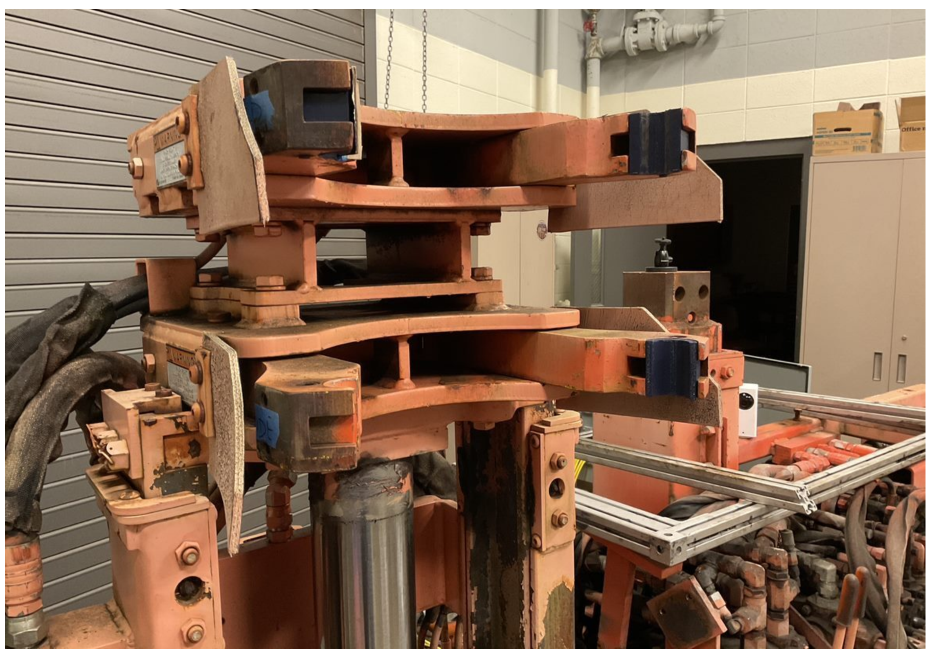


Figure 4.4: 3D-printed clamp inserts and drill guides

aluminum pieces, and it did not survive picking and moving PVC pipes. The research team worked closely with engineers at Fluidaire Automation to specify clamps for the end-of-arm tooling. Two Schunk clamps were purchased, shown in **Figure 4.5**, that were recommended to be used in tandem. These clamps are very heavy (approximately 9 pounds each) and reduce the robot's lift capacity at full extension if both are installed. The research team believes that a single clamp will be sufficient as long as the gripping area of the 8-foot bolts used for load testing is controlled carefully. Also shown in **Figure 4.5** is the 3D-printed fingers for the tooling. These are made from I-beam style brackets attached to the sliders of the clamps. The gripping fingers are a modified v-block design that grips the drill steel and bolt tightly. The v-block design is efficient in gripping round objects and is commonly used in machining. This design has held up very well to abuse during testing. Commonly, positioning is off while programming the arm's motions and small collisions have a large moment.

New finger designs incorporate reinforcements for weaknesses. The pictured fingers have been very resilient in testing. These designs will eventually be made from a more durable material when the design has been shown effective. There is a flexibility in the plastic that is desirable, which is not available in most metal materials. Traditional drill steel coupling using spring detents, or "wedding rings", can often be hard for human operators to separate. This project uses the new quick release design from Fletcher that only requires an 1/8 turn to couple and decouple. **Figure 4.6** is an image of the drill steel coupler used in this project. Because of this coupling, the robot does not need to turn the drill steel or pull the drill steel apart. The coupling can be engaged by the chuck when the bottom of the first drill steel is aligned in the drill guide and the second drill steel is placed into the first by the robot. When the chuck wrench connects to the bottom drill steel, the coupler will be locked. To unlock the coupler, the top drill needs only be held by the clamp, while the head reverses rotation, forcing the pieces apart.

The Schunk clamp, like most of their clamps with this strength, is designed to be fail-safe. Meaning, when the pneumatic line to the close side of the clamp loses pressure, the clamp will not open. Because this is a double-action clamp, both the open and close actions are powered, so the stock Air Control Unit on the robot was insufficient (**Figure 4.6a**). A new unit that will over-ride the fail-safe was put on the robot (**Figure 4.6b**). This air valve will push air to the close side of the clamp when energized and will push air to the open side in all other cases. This means that if the robot loses air pressure or power it will drop whatever it is holding. The hazard from a falling bolt is less than the potential hazard from the bolt swinging and colliding with pinning a person or limb. In the case of an accident the power can be cut, and the robot will let go of the bolt or drill steel.

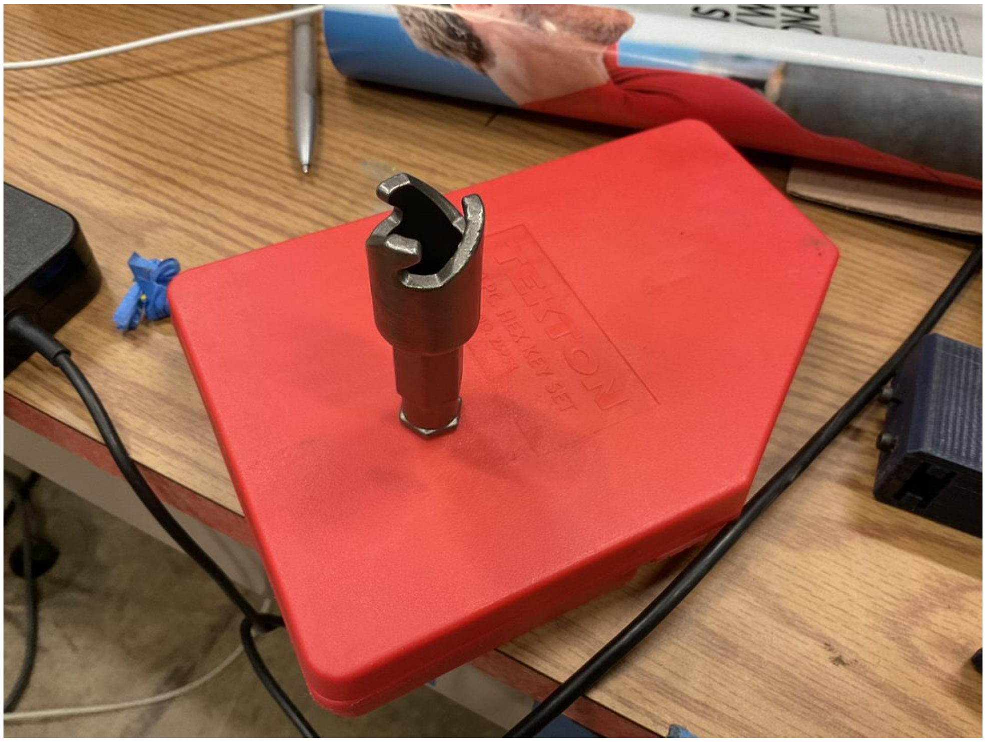
4.5 Bolt Module Setup

The descriptive study of the operator's direct motion pattern and roof-bolter operational stages is an important stage in specifying the level of autonomy of this designed system. The level of autonomy of the robot needs to be tailored to the requirements of the user. For this study, the robot executes tasks without continuous human interaction. The control mode of supervised autonomy seems to be the best strategy. Supervised autonomy makes it possible to modify the level of autonomy of the robotic system. However, for some tasks, like preventing a collision, a shared level of autonomy may be desirable. Shared-control methods can support the user in performing complex tasks, by building up the tasks in phases, wherein each phase has an individual set of controls.

To demonstrate the features of the roof-bolter environment, it is important to identify and define the actual goals. The task of placing the drill steel is composed of five parts. Inspired by observation of the strategies adopted by the roof-bolter operators, **Table 4.1** shows all five possible motion patterns of the roof-bolter operator. Analogous to the previous table, **Table 4.8** shows all possible roof-bolter operational stages, defined to plan the motion of the robot during task execution.

State	Description
Roof bolt ejection	The first state of the installation process involves the ejection of a roof bolt from the storage magazine
Roof bolt vertical placement	This state occurs when the bolt is placed at the bolt base. The robotic arm moves away.Once at the bolt base a small hydraulic jack and clamp arrangement rotates the roof bolt vertically.
Roof-bolter loading	This occurs when the roof-bolter extends the drill motor up so the roof bolt sits in the chuck. The robotic arm remains in the previous state. Once the roof bolt is seated, the bolt base releases the clamps on the roof bolt so the roof-bolter can assume the next roof-bolting installation process
Next installation position	The loaded roof-bolter assumes the following installation process. The robotic arm moves towards the storage magazine and grabs the specified chemical resin. The chemical resin is injected. The chemical resin can go off before the drill head rotates
Reload roof bolt	The robotic arm returns to its original position. Then moves towards the storage magazine and grabs a new bolt. Once in the bolt base the bolter docks in position to load the bolt

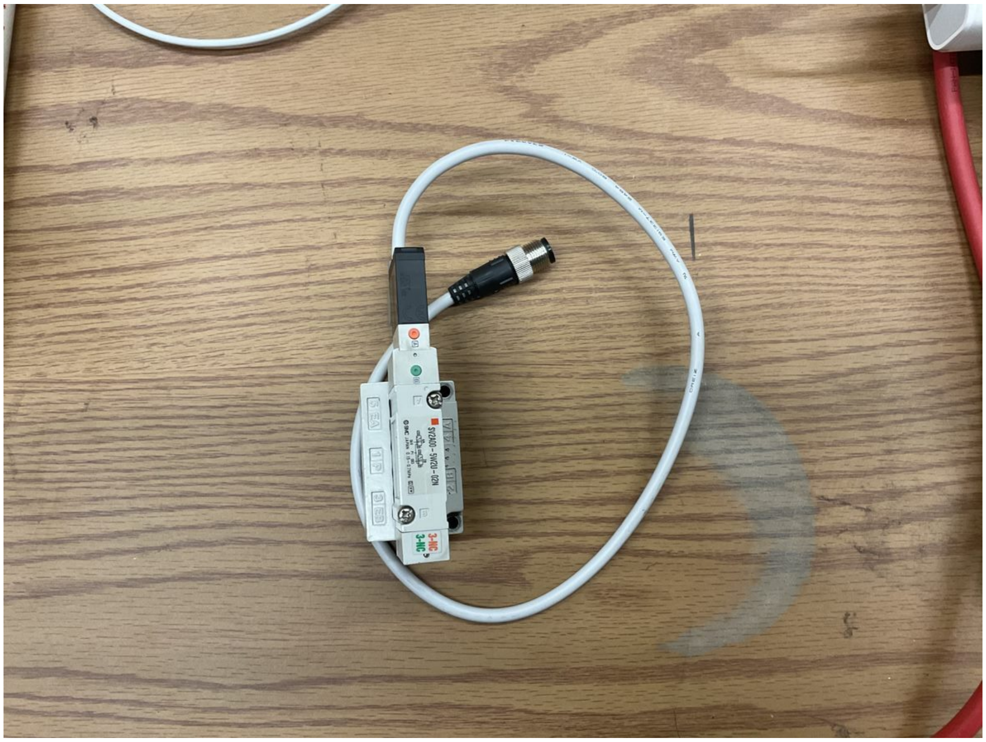
Table 4.1: Descriptive study of the roof-bolter operator's motion pattern



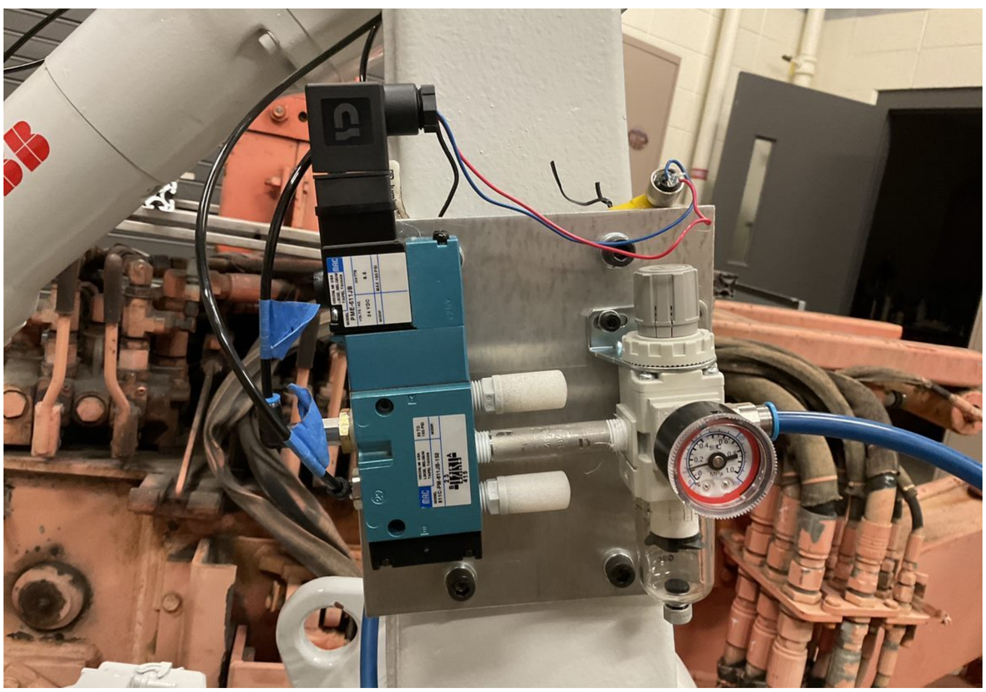
(a)

(b)

Figure 4.5: Drill steel quick coupling



(a) Primary air control unit



(b) New air control unit

Figure 4.6: Available air control units

State	Description
Broken	This state occurs when the bolter is recovering from a failure that will stop the bolter from operating
Delayed	This state occurs when an outside influence has prevented the bolter from operating
Bolting	This occurs when the bolter has completed bolting an area
Tramming	This occurs when the bolter has arrived at a new place to bolt
Waiting	This occurs when the bolt supposes that it will be able to tram to a place that requires bolting

Table 4.2: Descriptive study of the roof-bolter operational stages

4.6 Simulation Environment

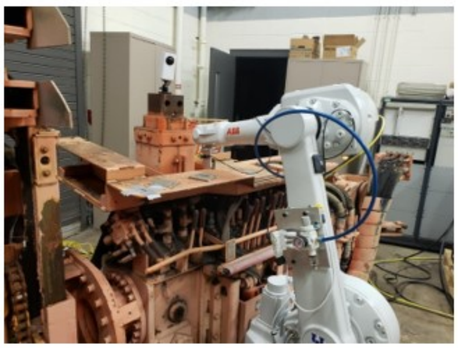
A roof-bolting scenario is set (**Figure 4.7**) in the ABB Robot Studio (robot simulator developed by ABB). The simulated roof-bolting scenario is constructed based on the actual roof-bolter at the University of Kentucky shown in **Figure 4.8**. The simulation phase of the automated roof-bolting project provides a representation of the planned autonomous roof-bolter lab structure. The simulation environment, incorporated by the IRB 1600 robotic arm and drill steel, is based on actual evaluations to develop the roof-bolter structure and other functional components. Combined with the specification, i.e., robot's arm reach and actual payload, the research team was able to define the limits for the system capabilities.

Development infrastructure

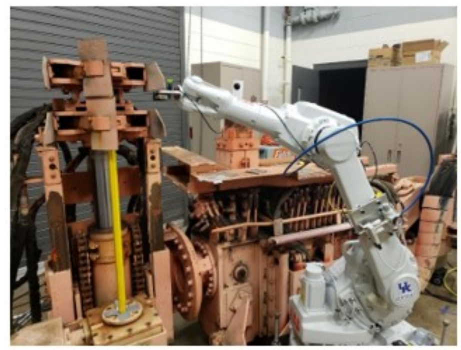
Aiming to facilitate the communication between the user and the developer, and considering the advantage of the familiarity that current developers have with them, Git and GitHub were used. For operators, usage, performance and installation of the updated libraries matter the most. The usage of the packages has been simplified by

(a)

(b)



(c)



(d)

Figure 4.7: Localization based on the 3D model of the roof bolt environment. The robot is picking up a drill bolt and placing it into the chuck

relying on program syntax similar to the movement patterns that the robot follows. Furthermore, good optimization is achieved by careful optimization of the package and by RAPID and C# implementation. The ease of installation lies in the use of a local repo from the central repo (git pull origin master).

4.7 Translating Human Picking Skills into Robotic Motion Patterns

Different motion patterns are developed and tested for the roof-bolting tasks. This is done by setting important waypoints as targets for the robot. Consequently, the robot follows the waypoints automatically. Once the motion patterns are set, the robot accurately and repeatedly executes the tasks. These motion patterns are implemented in RAPID (**Figure 4.9**). It is crucial to analyze how different levels of the location of the robotic arm affect the performance of the roof-bolting cycle. The algorithm uses the whole roof-bolting motion to generate a process (line 1). First, two positions

Figure 4.8: Actual roof-bolter located at the University of Kentucky, Rock Mechanics lab

are specified for the robot to reach. Then, the robot moves to the initial position (line 2) and grabs the drill steel (line 3), and finally it retracts the drill steel towards the drill head (line 4). Notably, the retract motion must be carefully designed to avoid the potential collision between the robot and the roof-bolter. Subsequently, the robot places the drill steel into the drill head (line 5). The robot reaches the positions only when the relative distance between the robot and the roof-bolter is correct. The program implements a general picking and placing drill-steel process, corresponding to **Figure 4.9**, and it is straightforward, extending to other processes in the whole task.

4.8 Implementation and Verification of Robot Motions

For validation, the simulation results are run on the actual roof-bolting system. The currently implemented robot motions include self-positioning, drill grabbing and drill plugging. The successful execution of commands by the robot generates feedback signals delivered to the HMI system. Upon completion of a task, a green light indicator is activated on the user interface. After the robot executes assigned commands, feedback information can be transmitted to the human operator to inform them of the task's status. It is possible to verify that the robot is at the correct position with self-positioning before performing the task.

Generate_Roof_Bolting_Motions

Input: A calibration pose cp, initial pose ip, grab pose gp, place pose pp, gripper close position gcp.
Result: The drill steel was successfully placed in the roof bolter.

1. *Calibrate(cp)*
2. *Move the robot to ip*
3. *GoPick(gp, gcp)*
4. *Retract(ip)*
5. *GoPlace(pp)*

Calibration(p)

6. *Move the robot to p.*
7. *Verify if the whole system is in the right position.*

GoPick(p, gcp)

8. *Move the robot to p.*
9. *Move the gripper to gcp.*

Retract(p)

10. *Move the robot to p.*

GoPlace(p)

11. *Move the robot to p.*
12. *Verify the drill steel is successfully placed inside the roof bolter.*

Figure 4.9: The pseudo-code for generating roof-bolting human motions

4.9 Discussion

One of the most challenging tasks of automating the operation of the roof-bolter is that the manipulator should perform the specified operations while in limited space. So, the placement of the robotic manipulator in the vehicle is crucial. The robotic arm should also be able to pick up and install longer-than-seam-height-bolts, both resin and mechanical, with the various ancillary parts required of roof-bolting. Its storage needs not be kept in the module, but arrangements are made to provide the module from onboard storage and minimize onboard storage re-provisioning.

4.10 Critical Milestones

The robotic arm installation project requires re-imagining the bolt installation procedure in terms of the dexterity of the human operator. Historically, locating the installation assembly relied on the operator. The basis of this project is to use an automated machine-positioning system, which is a 6-axis anthropomorphic robot in place of a human to handle the drill steels, bolts and other consumables. This robotic assembly will carry out the entire sequencing of the roof-bolting. The hydraulic system will be synchronized with the robot's operations. A human operator will be required to approve major operations, while also maintaining the ability to operate the robot and the hydraulic system. The only human interaction with the autonomous roof-bolter should be re-provisioning the onboard storage, maintenance and supervisory control of the machine (Jobes, 1990). A list of functional requirements that a picking-placing system should match is reported in the flowcharts of **Figure 4.10**. The complete developed system layout set at the University of Kentucky, Rock Mechanics laboratory, is presented in **Figure 4.11**. Observing student-human operators at the laboratory, and analyzing the video recording of skilled human operators, led to the design of a preliminary flowchart of the semi-autonomous roof-bolting cycle (**Figure 4.12**) and to the design of a schematic representation of the roof-bolter and robotic arm shared activities (**Figure 4.13**).

4.11 Conclusions

Mining is a rapidly growing industry and recent advances in engineering automation can substantially improve the safety of operations while increasing operational efficiency and production capabilities. This requires combining expertise from mining operations with control methods in robotics. Future work will focus on enabling automated equipment to dynamically adapt to changes in the environment, rather than executing pre-planned motions. It will also expand the proposed capabilities to tasks beyond roof-bolting, such as autonomous navigation and tool delivery.

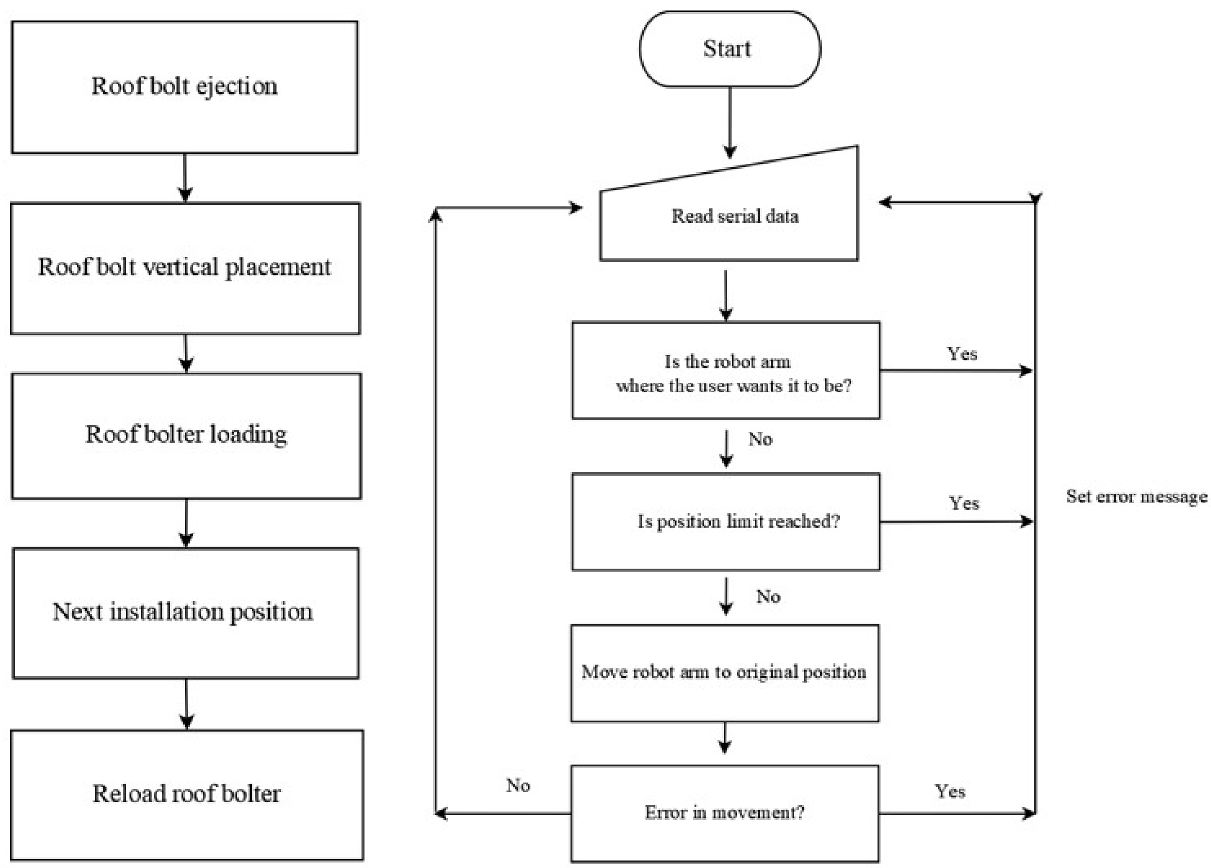


Figure 4.10: Flowchart of the human motion states (left) and the robotic arm controllers (right)

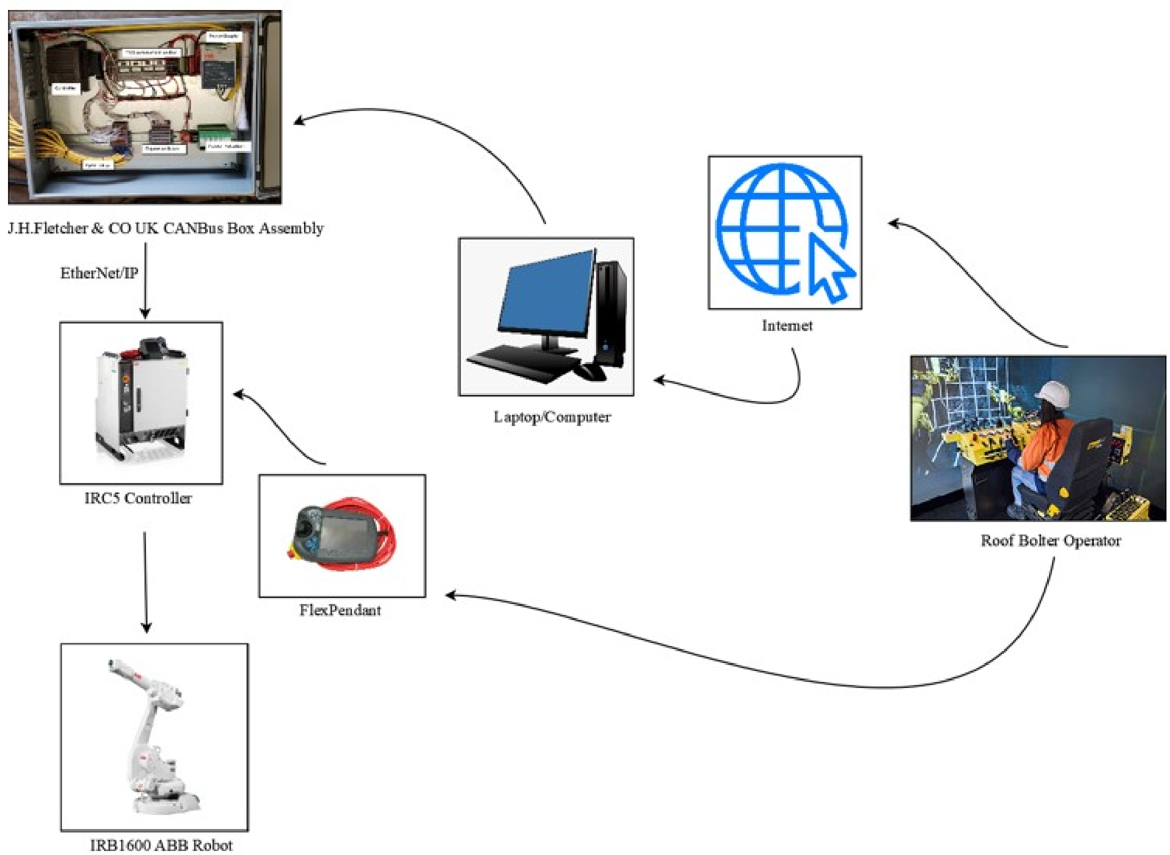


Figure 4.11: Schematic developed system layout at the University of Kentucky, Rock Mechanics laboratory

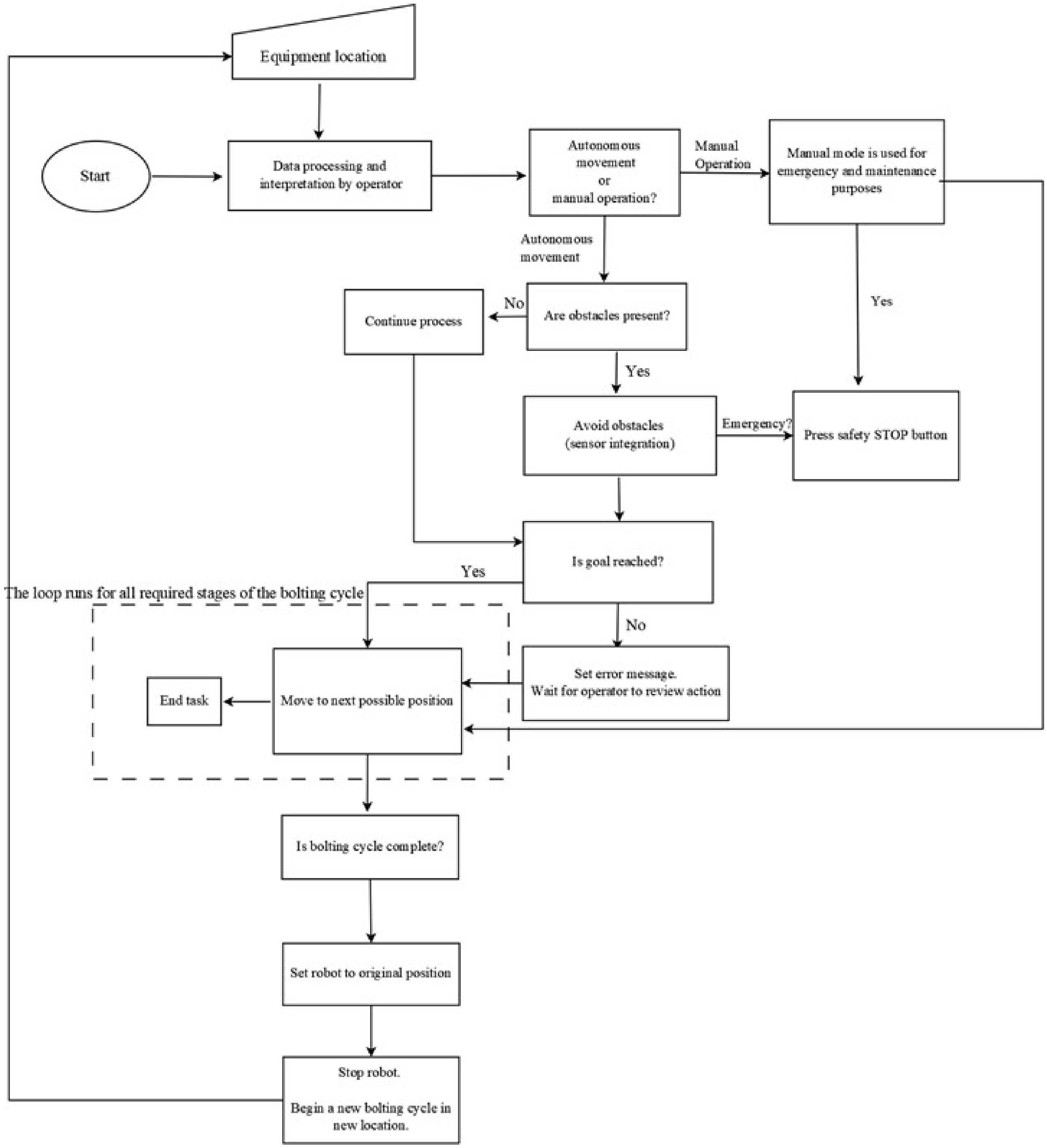


Figure 4.12: Preliminary flowchart of the semi-autonomous roof-bolting cycle

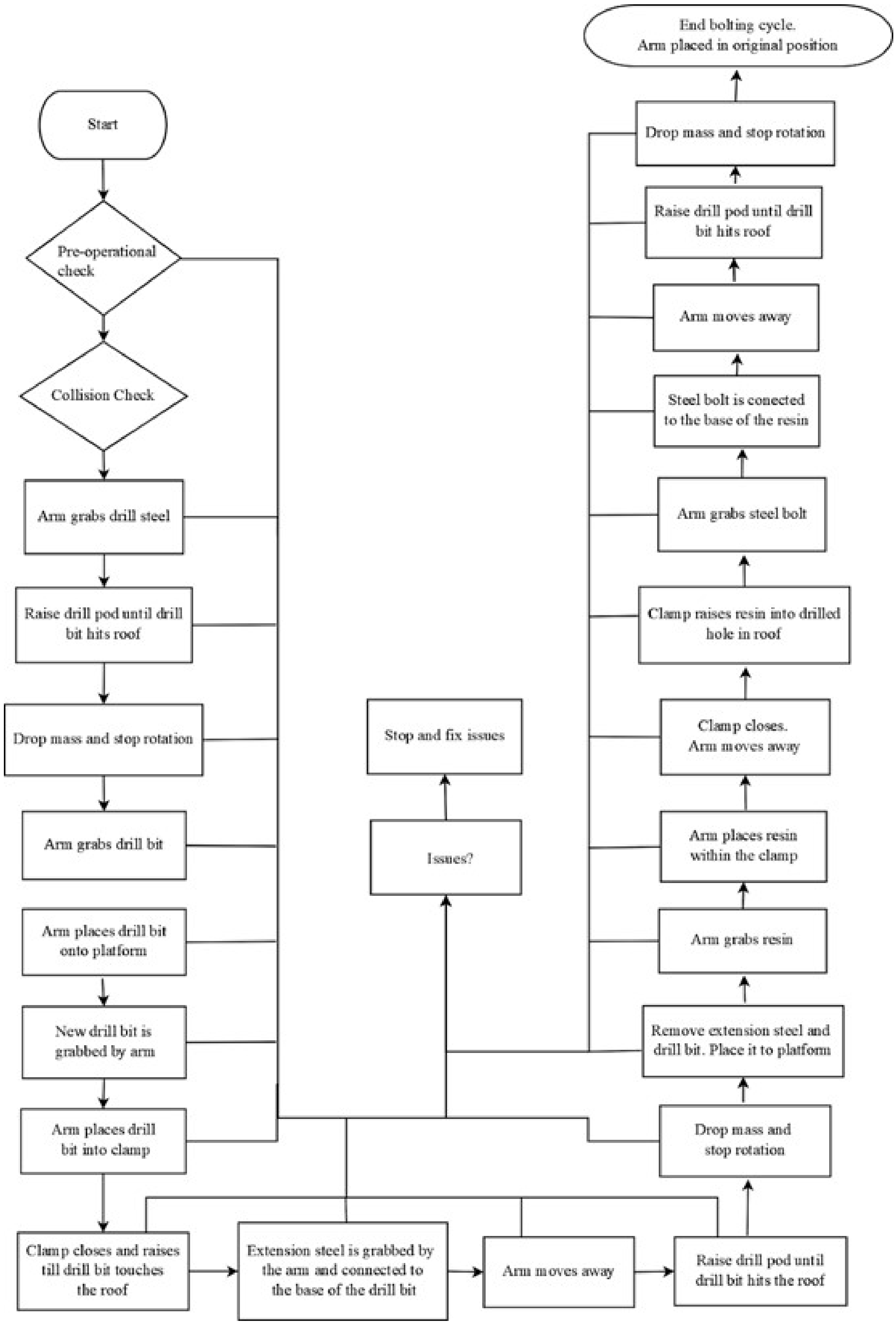


Figure 4.13: Schematic representation of the roof-bolter and robotic arm shared tasks

Chapter 5 Performance Evaluation

5.1 Project Overview

The primary goal of this prototype solution is to develop typical motions the robot will perform while in operation. The author verified and implemented the core robot motions by clearing the area of potential collisions. The implemented robot motions include steel manipulation. As described in previous chapters, navigation is limited to following a pre-defined path and collision avoidance while operating in fully autonomous mode rather than mapping and path-planning. The operator can easily switch into manual mode whenever necessary. One of the most challenging tasks of automating the bolting cycle of a roof-bolter is testing the control algorithms, as it proves to be a progression from simple scenarios to more complicated ones. In this chapter, the functionality of the prototype of the autonomous roof-bolter will be demonstrated.

5.2 Testing Scenarios

Test Pattern 1: Grasping Drill

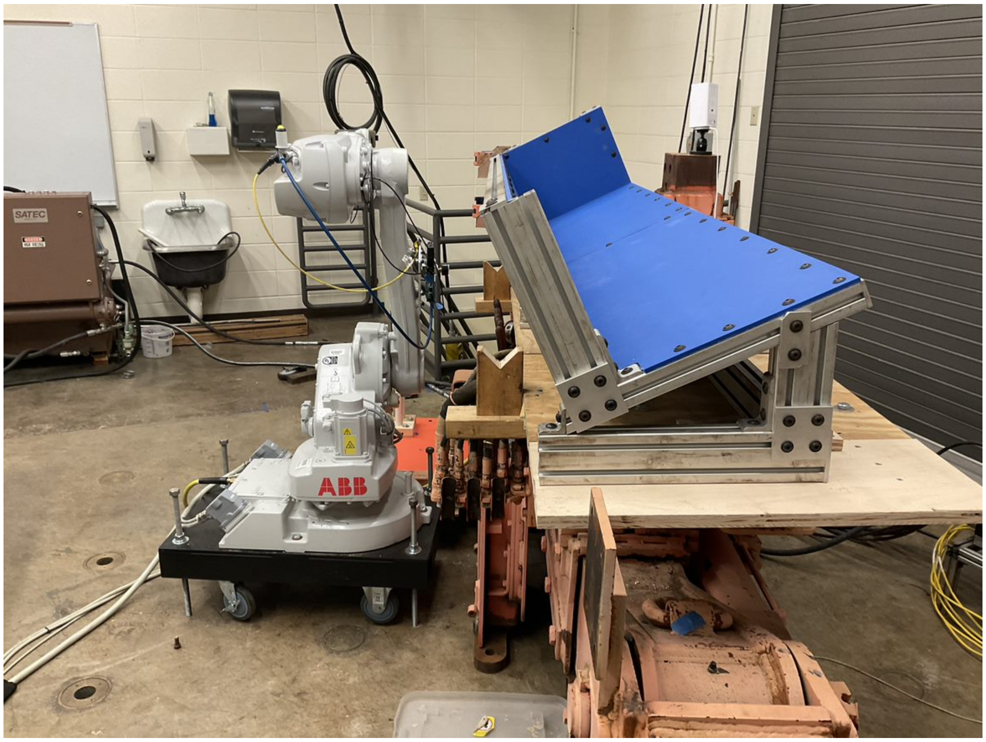
The drill steels are placed within a prototyped drill steel holder (**Figure 5.1**) at the designated locations, such that the robot can easily manipulate them in the confined space. The waypoints on the robot trajectories are carefully specified to avoid different obstacles of different sizes and shapes, like roof-bolter, power cables, etc. To close and open the robot gripper, a customized air valve is installed, and a signal is defined in the robot controller. Signals on the robot controller are the equivalent of tags on typical PLCs. Once the drill steel is grasped, the robot will follow a predefined trajectory to lift the drill steel up and plug the drill steel into the drill head.

During the development, the plastic gripper fingers may introduce noise into the grasp point. The author was uncertain that the current finger design will work for all operations and plans to manufacture metal fingers that will flex less. However, the flexibility in the prototype is required to account for the deviations in the algorithm. It is reasonable to expect that a machine in mining conditions will experience the deviations even with rigid fixtures.

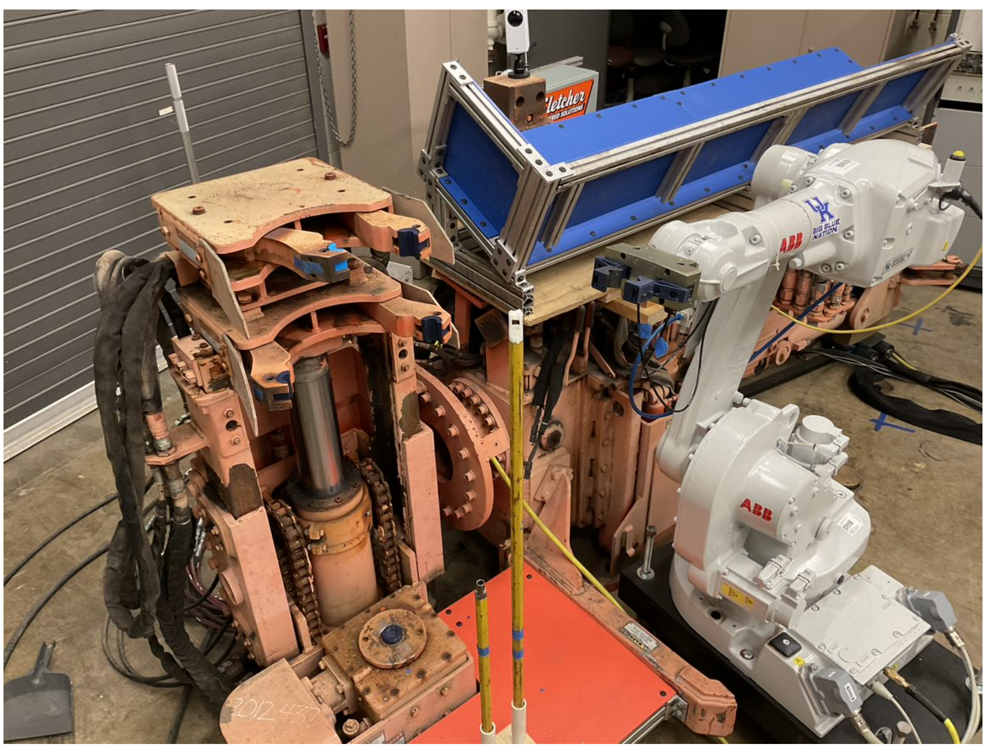
Test Pattern 2: Drill Placement

The initial plan to imitate human motions, placing the drill directly in the chuck, destroyed several plastic gripper fingers. Additionally, variations in location and orientation of the steel when grasped resulted in the drill missing the chuck. Moreover, the chuck is moving, and using the hydraulics alone, it is difficult to put into a perfectly repeatable position. The research team found it significantly more robust to position the drill on the holder (**Figure 5.2**). While this motion would be complex for a human, since it requires targeting a point in space between two moving jaws, it is ideal for the robot. The grip location along the length of the drill is still a variable because collisions must be avoided with the roof.

However, once in the clamps, the hydraulics alone can chuck the steel. While the robot is accurate in positioning, its joint actuators are not pliable via outside forces. In this case, the robot is handing the steel to a clamp, which is much like handing a broom (or any long rigid bar) to someone else. Humans will adjust the angles of their wrists, elbows, shoulders, etc. based on the force exerted by the other human when they grasp the same object. The outside forces will not move the robot's joints, and if the force exceeds the robot's holding strength, the robot will move and be damaged. The research team plans to replace the plastic customized gripper with a metal one; one challenge will be making sure the clamps of the roof-bolter can safely grasp the drill steel while held by the robot. The research team is still determining where the point of failure should be located. The current 3D-printed fingers will break much sooner than the servo motors. As will be discussed later, the metal clamps in the hydraulics are replaced with 3D-printed inserts. Either the inserts or the fingers are the logical points of failure, but this will be determined in further testing.



(a)



(b)

Figure 5.1: A side view of the prototype drill steel holder and coupled bolts

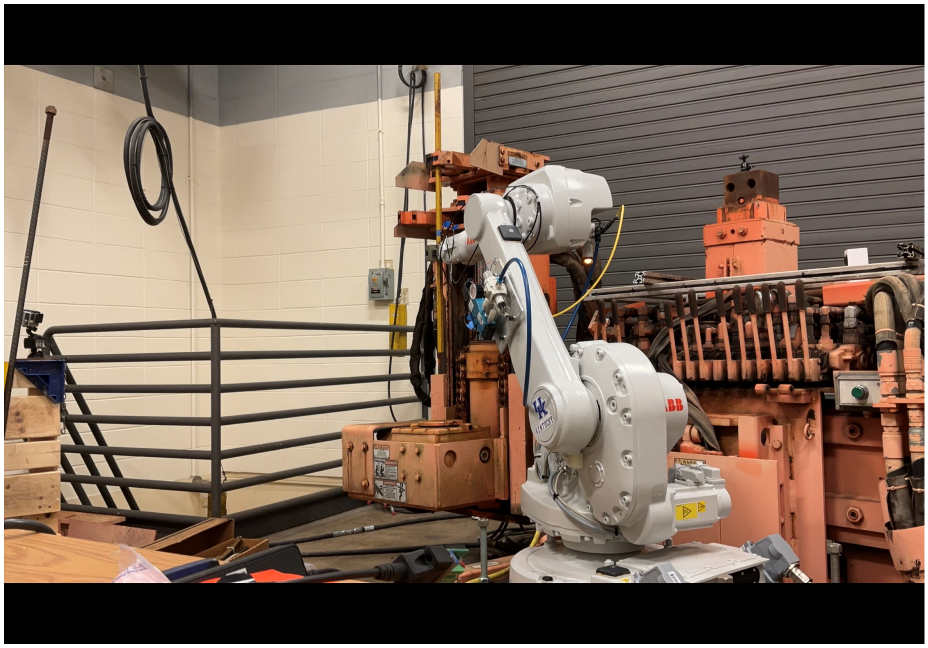


Figure 5.2: The robot accurately places the drill steel into the clamps. On the contrary, the robot cannot accurately place the drill steel into the chuck

Test Pattern 3: Drill Replacement

The last step is to remove the drill-steel from the drill area. This trajectory is the reversed installation trajectory. Yet, because of the mentioned variation in the location of the hydraulic head, there is variation in the grasp point on the steel. This variation needs to be accounted for in the drill-steel storage, allowing the arm to "drop" the steel into storage. For this reason, storing the drill-steels vertically in the prototype holders was chosen.

The other motions that the robot will perform are variations on these motions. They are to grasp from a predictable position, hand off to the hydraulics, clear obstacles, and return fixtures to holders. Major, yet to be developed, patterns are installing the resin-injection system and grasping the bolts. The resin-injection system, and the other fixture that needs to be returned will also be stored vertically. The research team did investigate magnetic mounts and other clamping fixtures. These fixtures all have similar problems to the clamps on the hydraulics. The main goal is to minimize the amount of and opportunity for outside forces to act on the robot, especially while it is in motion.

Using time series analysis to identify poor hydraulic performance

In this experiment, time series analysis was used to identify issues associated with poor hydraulic performance. A laser distance meter was placed under the roof-bolter pod, calculating the vertical distance between the floor and the pod for each drilling cycle. Here, the drilling cycle is divided into the Insert Bolt cycle and Couple Bolt cycle. Each cycle is completed every 15 seconds. The distance was measured in inches. **Table 5.1** summarizes the acquired data. The set of data consists of $n = 32$ total measurements. Indications of complex, non-stationary behavior can be visualized on **Figure 5.3**, as the mean and standard deviation are not constant over time.

Table 5.1: Summary of studied data-sets

	Insert Bolts (in)	**Couple Bolts (in)**
10/25/2021	8.875	8.875
	8.625	9.062
	8.437	8.812
	7.750	8.062
	7.250	7.687
	6.937	7.000
	6.125	6.314
	6.000	6.000
10/27/2021	8.875	8.875
	8.687	9.062
	8.500	8.625
	7.937	8.187
	7.273	7.750
	6.812	7.273
	6.314	6.437
	5.875	5.937

The trend present in the data set must be carefully examined. Validation measurement formulas were used to provide an evaluation of the statistical behavior of the system. The tested equation was the Pearsons's correlation coefficient (r_s). The Pearson's correlation is frequently used to measure the degree to which two variables are correlated. The closer the Pearson's product is to 1 or -1, the more accurate the linear fit (**Figure 5.5**). **Figure 5.4** provides another indication that there is no apparent pattern in the data points, and therefore, there is little correlation between data points.

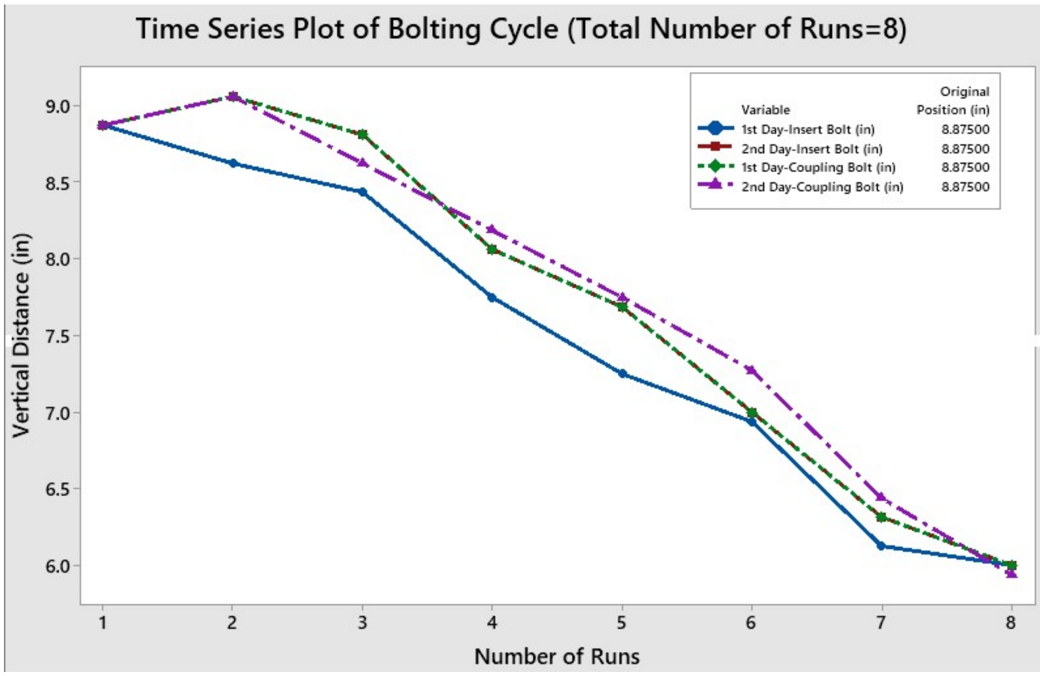


Figure 5.3: Plot of the measured vertical distance (in) as per bolting cycle, respectively. Trends are present for each group of data

The fact that vertical distance between the floor and the pod decreases over the course of time for each drilling cycle indicates serious issues associated with inadequate hydraulic performance. Those problems can be attributed to (a) poor resistance of working fluids, and associated decreased load-bearing ability, (b) the presence of leakage, (c) the hydraulic unit is sensitive to temperature changes, and (d) a pump not suitable for long-distance transition, hence requiring a higher applied hydraulic energy.

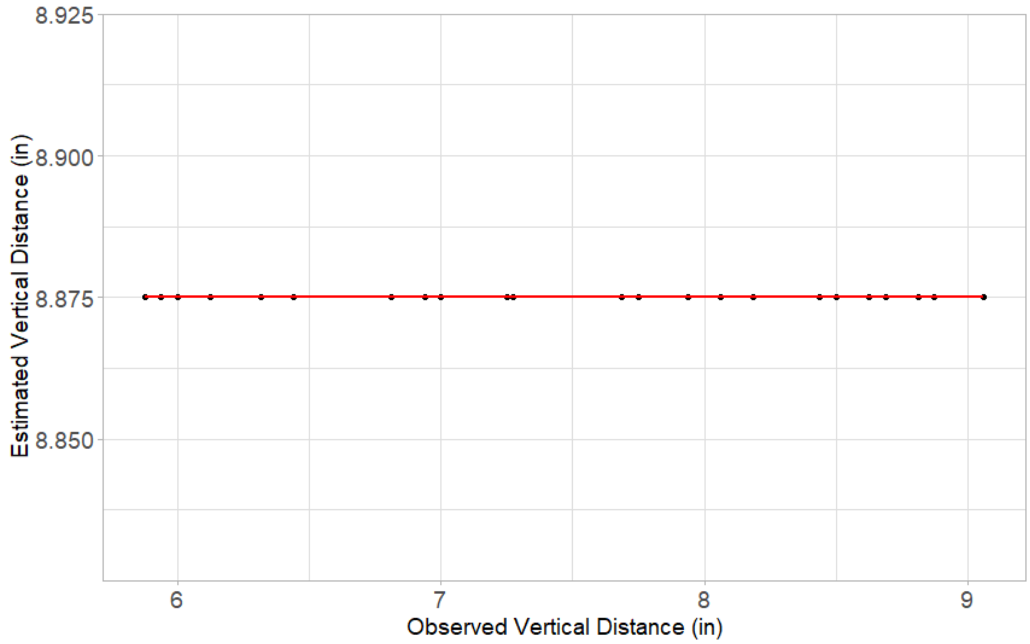


Figure 5.4: Scatter plot of the vertical distance (in) original and estimated values. The estimated value is 8.875 in, which is the position where the pod needs to be for every drilling cycle to begin

Correlations

	Original Position (in)	1st Day-Insert Bolt (in)	2nd Day-Insert Bolt (in)	1st Day-Coupling Bolt (in)
1st Day-Insert Bolt (in)	0.252			
2nd Day-Insert Bolt (in)	0.152	0.995		
1st Day-Coupling Bolt (in)	0.199	0.989	0.991	
2nd Day-Coupling Bolt (in)	0.138	0.983	0.987	0.994

Figure 5.5: Pearson's correlation chart

5.3 Developing HCI for Machine Operator

The Parker iQAN touch screen is the primary Human-Computer Interaction (HCI) device for the machine operator. The integration of iQAN and the ABB robot controller allows the operator to send commands both to the robot arm and the roof-bolter (**Figure 5.6 - Figure 5.13**). Two HCIs are being developed in parallel tracks. The first HCI is the C# based system that is purely for development purposes, running on the computer and bypassing much of the communication. The second HCI is an interface for the research team. This interface isolates specific CAN messages and robot signals to particular buttons and screens with information about current actions and communication. The primary purpose of this display is for development, demonstration, and timing. As the development total sequence progresses, groups of individual commands from the research team's interface are transferred to the automatic interface (**Figure 5.8**). An example in this grouping is "Place Drill"; this performs the following actions:

(i) Open the upper clamp and drill guides.

(ii) Move the drill chuck to the bottom position.

(iii) Pick the drill steel from the holder and move it to the center of the clamp.

(iv) Close the top clamp.

(v) Move the robot safely away.

(vi) Close the guide clamp.

(vii) Rotate and lift the chuck slowly.

(viii) Open the top clamp.

As discussed in the previous report, the human operator will be needed to authorize the next grouping of actions. This interface is developing to give the operator the flexibility with the hydraulics and the robot, while not overgenerating options.

5.4 Integrate Individual Actions, Bolt Module and HCI

The robot actions need to coordinate closely with the roof-bolter's hydraulic actions. The HCI is implemented on the PLC to control both the robot and the roof-bolter through IQAN. There are several ongoing communications that are not seen by the user. One example is a "handshake" communication between the robot and the PLC. The handshake works similarly to a heartbeat that is typically used when integrating two systems. Heartbeats typically work by one system creating a message that is viewable by the second system, and the second system keeps track of the time between signals. If the time between signals exceeds a threshold, then the first system is no longer available. Because both systems have control of various functions in this application, both the robot controller and the PLC would have to implement heartbeats and track the other system. The heartbeat cannot be made only via the robot controller because the robot tasks could take longer than a reasonable timeout.

The handshake works in a slightly different way. A CAN message is generated by the PLC, and this is translated by the Anybus into a signal on the robot controller. The robot controller has a subroutine that triggers on the signal change, and it toggles the signal back to the original state. That toggle is translated by the Anybus into a CAN message. Similarly, that CAN messages toggles an internal digital input in the PLC and the messages continue being passed back and forth, rather than blindly reporting.

The robot controller is setup with a listing of different signals for triggering RAPID code, causing the robot to do different tasks, e.g., grabbing the drill, lifting, plugging the drill. The signals correspond to different mappings on the IQAN message frame. **Figure 5.14** shows frames of a demonstration video of delivering the drill to the roof-bolter and performing a drill motion.

All commands of the operation are controlled by the HCI. As this development progresses, more communication channels between the robot and the PLC are being added. For example, the PLC needs to know when the robot has finished its particular task. But this cannot be done with a generic "completed" signal; the signals need to be specific to each task to avoid confusion between the robot controller and the

PLC. Furthermore, more information between the robot and the roof-bolter needs to be added, e.g., the robot positions, velocities, and acceleration.

5.5 System Integration Development

Practical software integration activities started with lower-level integration practices. This approach allowed for verification of the correctly implemented software code development and validation of the significant system functionalities. Later in the integration phase, test plans and procedures were developed to test the designed autonomous roof-bolting cycle. When necessary, integration tests were rerun. From an academic standpoint, the execution of the integration plans was responsive to the project's needs. Each step was reviewed and updated to reflect the altering project priorities and requirements.

A critical element of this thesis was the development of the Gateway component, which provides the user interface and central location of admission into the system for operators. **Figure 5.15** shows an example of the function groups that have been developed to control the functions from the HCI using the Anybus Configuration Manager. In order to exchange data signals, the Ethernet network reads and writes the data into memory addresses. Those addresses have been first specified by the Anybus Configuration Manager - Communicator RS232/422/485. Finally, the assigned memory addresses are exchanged with the subnetwork. This example group is broken into consuming and production CAN messages that are either causing direct action from the PLC or are communicating action to procedures that are written in ABB's RAPID language, stored in the robot controller. Here, the Anybus Communicator - EtherNet/IP, a hardware created by HMS, is used to connect and map non-networked industrial devices and equipment to EtherNet/IP. The Communicator can transform a majority of serial protocol (i.e, ModBus RTU, ASCII, etc.) to proprietary Query/Response or Produce/Consume protocol. The product consists of a connector and a communication processor. This device requires no hardware or software changes for the connected automation device.

5.6 Discussion

Modern mining industries are currently adopting the innovative idea of developing and implementing intelligent autonomous systems: modern learning algorithms (i.e., hybrid-neural, deep learning, and convolution networks), advanced computer hardware, and software aid in automating complex tasks and operations. In the last few decades, the U.S. coal industry has been more interested than ever in employing fully autonomous, semi-autonomous face equipment and tele-operated vehicles. All of these technological advancements encourage the idea of creating an efficient, effective, safer, and sustainable mine.

Amid the recent advancements in underground machine operation automation (i.e., LHD automation) is roof-bolter automation. Drilling and installing bolts in the underground coal roof is a highly cost-intensive process in terms of capital and operational cost per ton with equipment, making the ergonomic critical (efficient design and real-time performance evaluation). Modern roof-bolter models are required to understand the nearby environment, recognize and interact with neighbor face equipment, and overall enhance operational automation (Peng et al., 2019).

Ensuring the miner's safety is the pivotal factor in adopting autonomous solutions in underground mines. Deep underground mining is becoming the trend, not only of coal but of the metal mines as well. Therefore, it is important to overcome the disadvantages of traditional underground mining methods, such as frequently changing geological and geomorphic environment, high safety risks (i.e., tunnel collapse, roof falls, land subsidence, machine collision, etc.), and severe health risks (i.e., respiratory diseases such as silicosis, pneumoconiosis, etc. (Rahimi et al., 2021)). An increasing number of countries, such as Canada, Finland and Sweden, are currently collaborating with autonomous solution companies to develop customized autonomous heavy mining equipment to operate intelligent and autonomous mines. More and more mining companies are developing a serious interest in autonomous technology. For example, according to the Canadian government's 2050 long-range plan, Canada is planning on transforming one of its underground mines in the northern part of the country into an autonomous mine, meaning that all devices will be controlled from Sudbury via satellite (Walker, 2012). Another example is the Grountecknik 2000 strategic plan that is carried out in Finland. According to the program, veteran mining companies like Atlas Copco are actively developing a series of intelligent underground mining equipment and their related control systems Ralston et al. (2014). Furthermore, companies like Rio Tinto in Australia have already incorporated self-driving vehicles in their operations. In the U.S., J.H. Fletcher Co. is designing custom roof-bolter models for various underground conditions.

Yet, autonomous drilling requires that the software and hardware solution adapt itself to unexpected situations as such that can be found in an underground coal environment. Moreover, the functions to be automated require careful consideration of the capabilities and limitations of humans (Lynas and Horberry, 2011).

The robotic arm installation project requires re-imagining the bolt installation procedure on the dexterity of the human operator. Locating the installation assembly relies on the operator or the automated machine-positioning system. This robotic assembly will be able to carry out the entire sequencing of the roof-bolting. The hydraulic system will be synchronized with the robot's operations. A human operator will be required to approve major operations, while also maintaining the ability to operate the robot and the hydraulic system. The only human interaction in the autonomous roof-bolter should be the re-provisioning of the onboard storage, maintenance, and supervisory control of the machine. There are enough literature publications concerning the future of the mining sector. However, these publications are limited in covering only specific aspects of implementing a robotic system into a heavy hydraulic machine. This research offers an opportunity for the mining community to gain information about the elements of developing and testing the autonomous roof-bolter in a lab-scale setup.

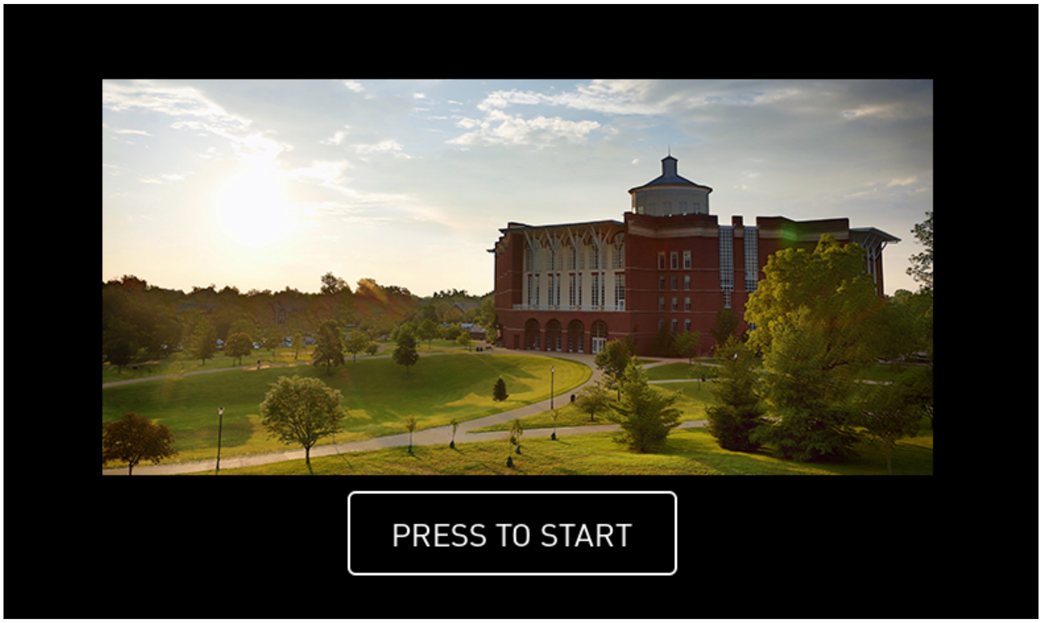


Figure 5.6: Touchscreen HCI for the Automatic Processes - Menu

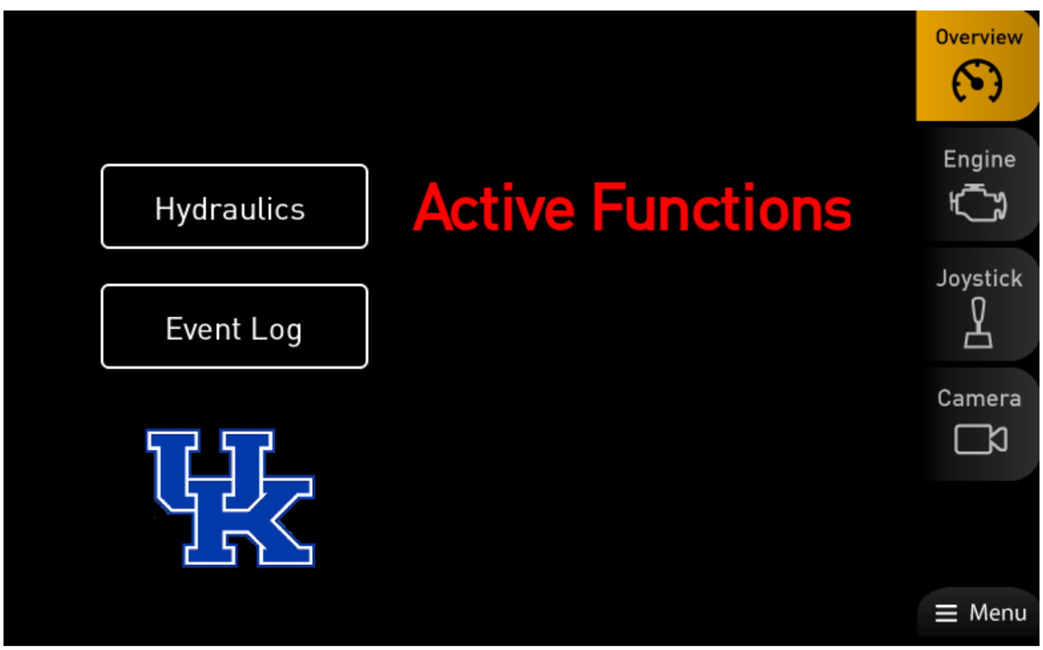


Figure 5.7: HCI Overview - Press Hydraulics to activate the roof-bolter's functions

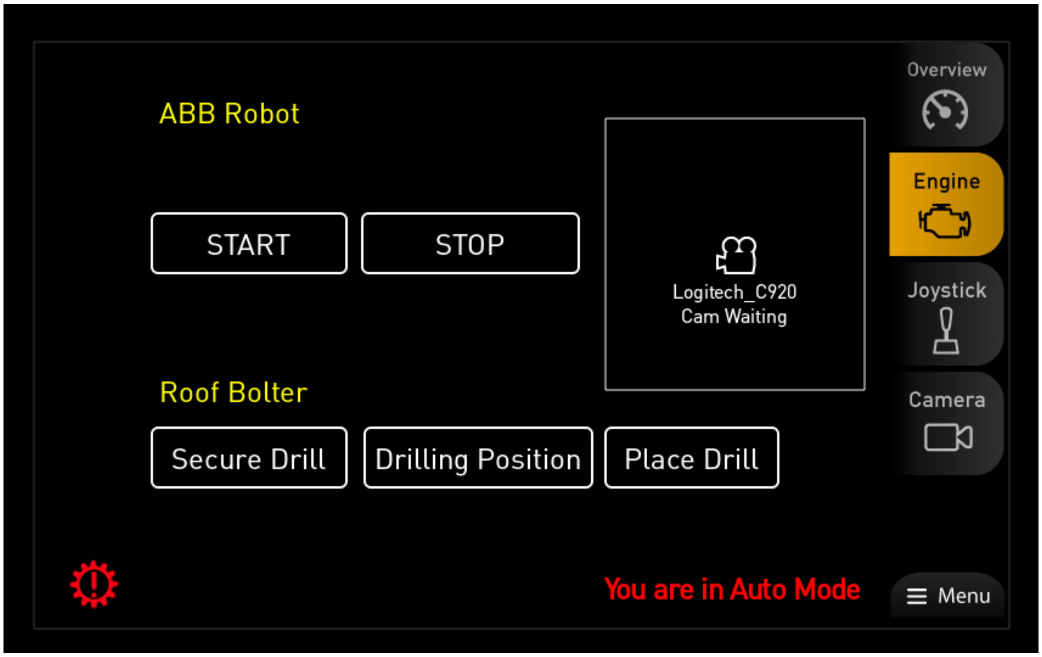


Figure 5.8: HCI Engine - Control and monitor the robotic and hydraulic tasks

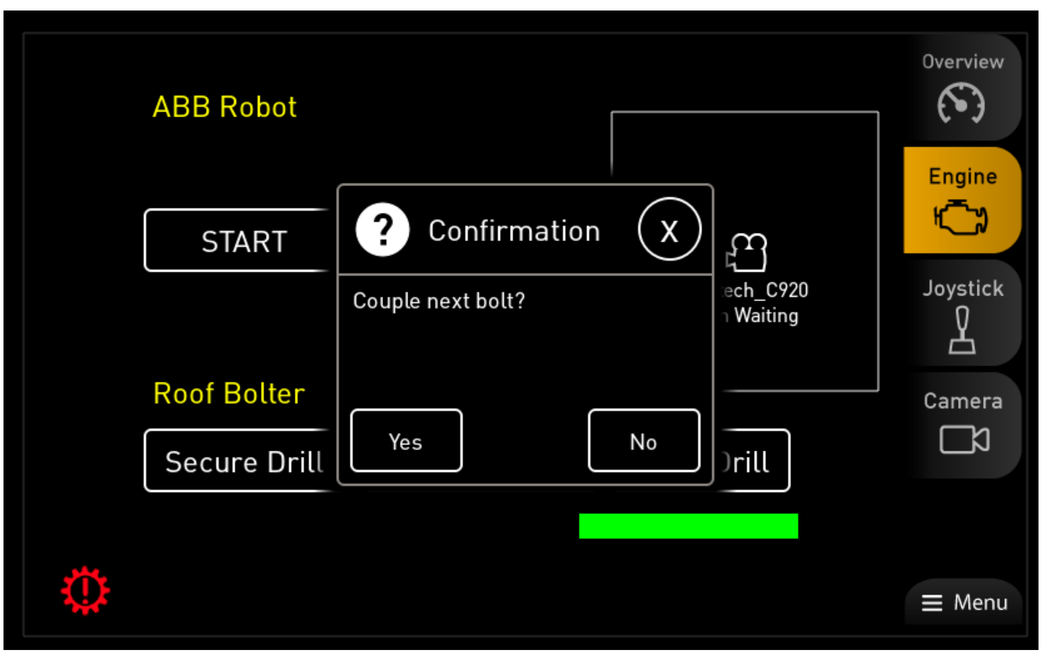


Figure 5.9: HCI Engine - Press Yes if coupling is required. Press No to continue with the bolting cycle

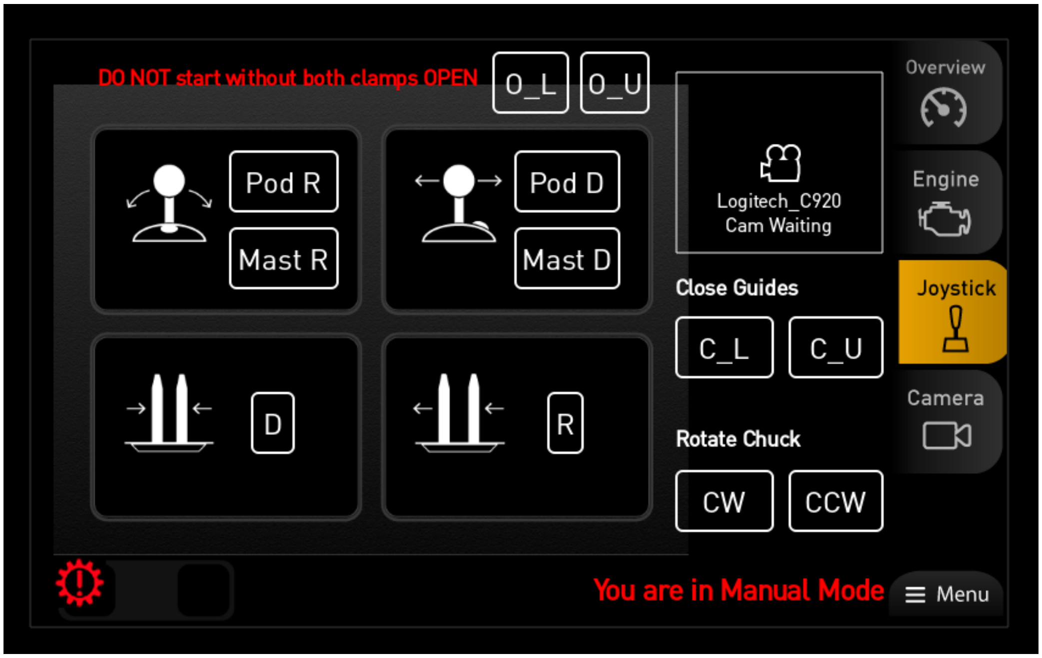


Figure 5.10: HCI Joystick - Control and monitor the hydraulic function manual. The user can use the designed push buttons or, alternatively, use the joystick (LC5)

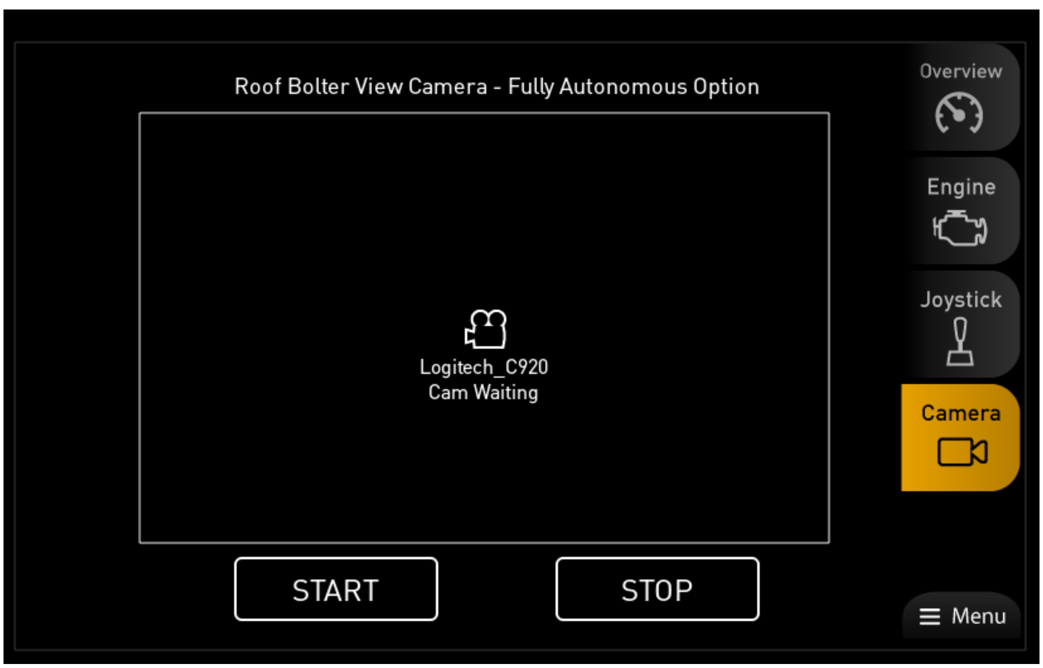


Figure 5.11: HCI Camera - View of the autonomous roof-bolter. Press START to begin a fully autonomous bolting cycle. Press STOP to end task. Camera is at wait state

Figure 5.12: HCI Menu - The user can overview the system properties, adjust and select desired preferences

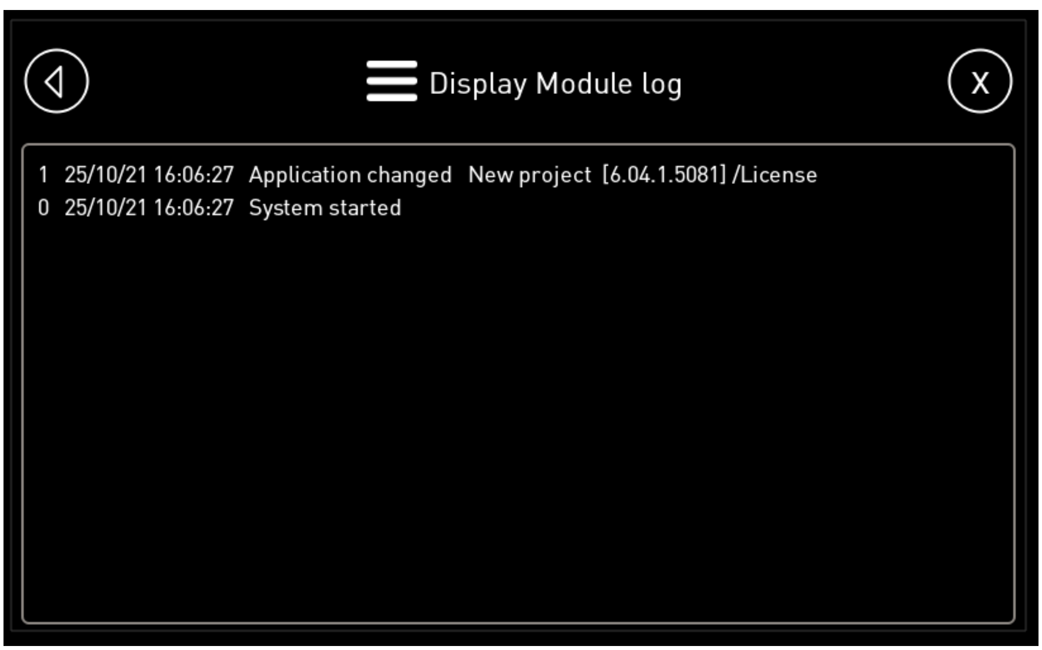
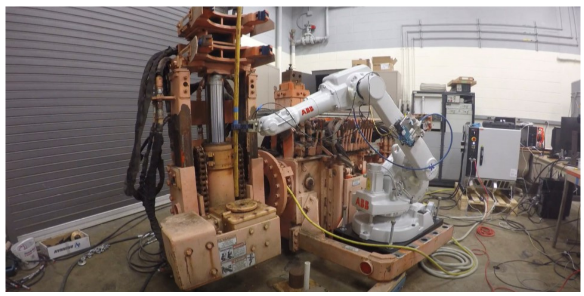


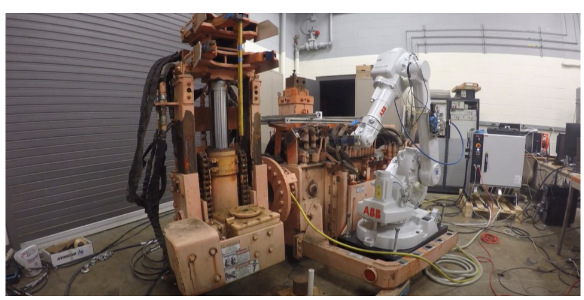
Figure 5.13: HCI Event Log - Display module log

(a) Pick Drill



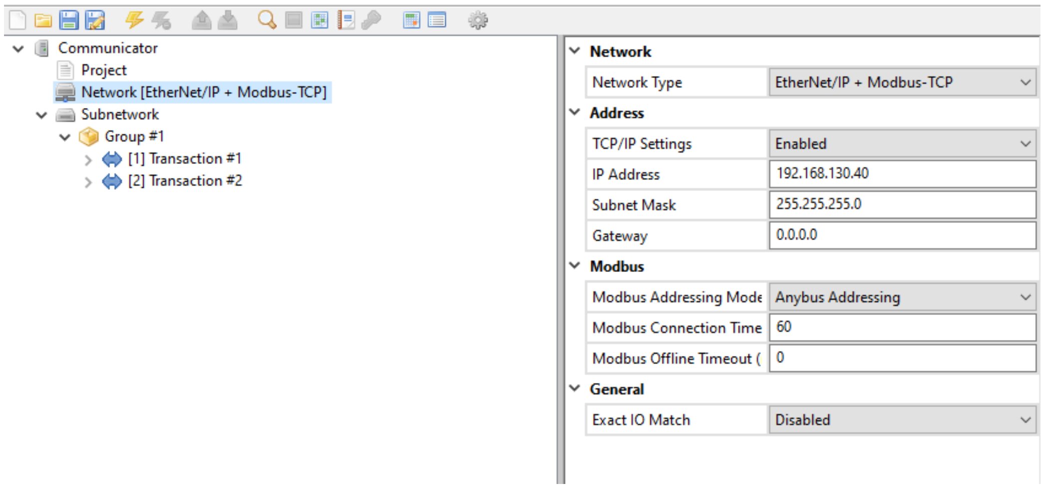
(b) Place Drill on the roof-bolter

(c) Raise Base

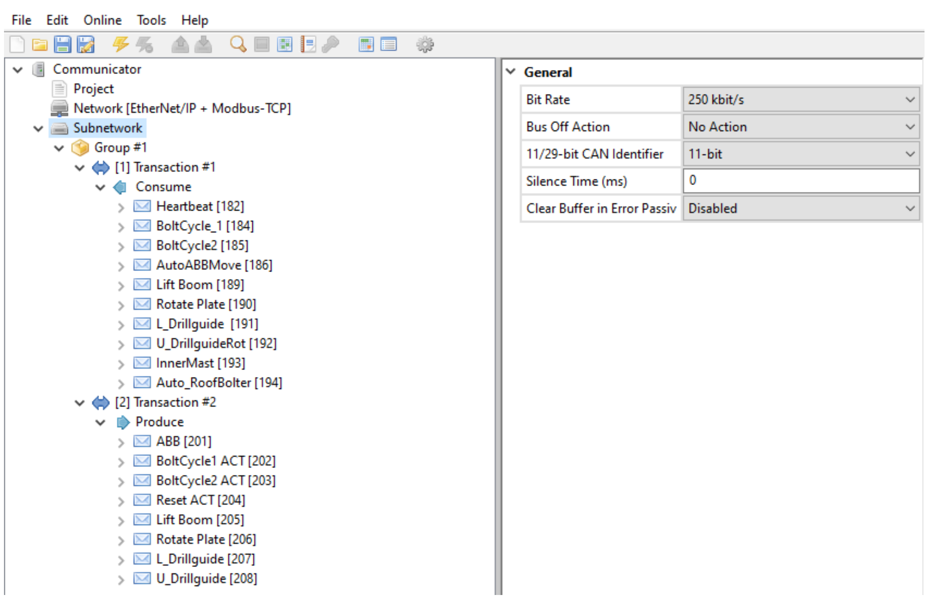


(d) Perform Drill Operation

Figure 5.14: Drill operation performed by the ABB robot arm and roof-bolter



(a) Network IP Adress: 192.168.130.40 and Subnet Mask: 255.2555.255.0



(b) Bit Rate: 250kbits/s and 11-bit CAN identifier

Figure 5.15: Example of the function group in the Anybus Configuration Manager architecture

Chapter 6 Conclusions and Recommendations

6.1 Conclusions

In conclusion, this thesis has presented the need to develop the autonomous roof-bolter that can enhance the miner's safety, aid in the continuing increase in productivity, and reduce operational costs for the current and future mining conditions. Based on the conclusions mentioned in previous chapters of this thesis, the following overall conclusions are drawn:

(i) The autonomous roof-bolter presented, has two main objectives: to reflect current underground roof-bolter practices and provide an insight on how the autonomous roof-bolter can enhance miner safety.

(ii) A user center GUI has been developed for a human user to control and monitor the autonomous roof-bolter by implementing the Parker MD-4 touchscreen. Visual alert signals will pop-up every time the hydraulic system will complete a bolting cycle. Other visual and auditory signals have been omitted from the HMI since the whole system is still operating in a lab-setup.

(iii) Once the failure detection systems have been found to be robust, they will be made more complex and autonomous. Efforts would be made to incorporate preventive actions and actively check for impending failures. These computer programs will also allow the operator to edit the operational parameters on the fly without having the system go out of operation.

(iv) Laboratory tests have been carried out in a mock mine environment to assess the performance of the developed system; several different scenarios, simulating joint missions that a roof-bolter needs to undertake in an underground coal mine, have been considered.

(v) Results of this prototype design of the autonomous roof-bolter show great operational potential for future employment in underground coal mines.

6.2 Limitations and Recommendations

The autonomous roof-bolter design will require several different areas of future research and continued development. Developing a suitable and consistent architecture has significant implications for the future employment of proficient and reliable autonomous roof-bolting system that provides the foundation for more rapid and efficient development. With the modern advances on the level of autonomy, the uncertainty of problems in the present system should be solved in advance to achieve different and more robust functionalities.

On the other hand, due to the increasingly complex performance of the hardware and software in the system, the system is prone to numerous malfunctioning system failures that have not been considered in advance. With the continuous improvements of artificial intelligence technology, the mining industry has been trying to employ equipment that is going to be able to make smart decisions on their own based on the changing environment. Future mining systems, including the autonomous roof-bolter, should establish new mining-suitable computer models that will actively learn from the surrounding underground environment and generate a scenario optimization mechanism, suitable for the continuously changing face.

Recommendations for the lab-scaled autonomous roof-bolting system are listed below:

(i) Improving the currently developed GUI would ultimately guarantee the secure control of the autonomous system. In addition, advanced collision-avoidance algorithms need to be included to enhance safety. Finally, vision cameras coupled on the front of the robotic arm and the roof-bolter, will eventually improve the bolting cycle by allowing the user to navigate the roof-bolter, providing it with real-time position, allowing for manual control when necessary.

(ii) Further complex trials of the various bolting scenarios need to be thoroughly studied to better understand the issues modern roof-bolter operators face while on the job. Those additional experimental tests will enable debugging and spotting mechanical problems in the system, while at the same time identifying potentially dangerous scenarios.

(iii) Investigate the possibility of a robust human-machine integration mechanism design based on collaboration. A robust safety human-machine interface design should be fostered to avoid completely uncontrollable situations.

(iv) The robotic arm bolter installation project requires re-imagining the bolt installation procedure on the dexterity of the human operator. This means that it is necessary to provide awareness of the benefits of using the autonomous roof-bolter, while providing specified training for roof-bolter operators.

References

ABB (2015). Yumi - creating an automated future together. `http://new.abb.com/products/robotics/yumi`.

Abbink, D. A. and Mulder, M. (2009). Exploring the dimensions of haptic feedback support in manual control. *Journal of Computing and Information Science in Engineering*, 9(1):10–18.

Abbink, D. A., Mulder, M., and Boer, E. R. (2012). Haptic shared control: smoothly shifting control authority? *Cognition, Technology & Work*, 14(1):19–28.

Ainsworth, S., Gero, A., Parobeck, P., and Tomb, T. (1995). Quartz exposure levels in the underground and surface coal mining industry. *American Industrial Hygiene Association Journal*, 56(10):1002–1007.

Al-Aani, F. S. (2020). *CAN bus technology for agricultural machine management research and undergraduate education*. PhD thesis, Iowa State University.

Argall, B. D., Browning, B., and Veloso, M. M. (2011). Teacher feedback to scaffold and refine demonstrated motion primitives on a mobile robot. *Robotics and Autonomous Systems*, 59(3-4):243–255.

Azman, A. S., Yantek, D., and Alcorn, L. (2012). Evaluations of a noise control for roof bolting machines. *Mining Engineering*, 64(12):64.

Bathopele Mine, Rustenburg, S. A. (2020). Mining technology. `https://www.miningtechnology.com/projects/bathopele-mine-rustenburg/`.

Beck, T. and Goodman, G. (2008). Mining publication: Evaluation of dust exposures associated with mist drilling technology for roof bolters. *Mining Engineering*, 60(12):35–39.

Beck, T. W. (2012). Dust capture performance of a water exhaust conditioner for roof bolting machines. *Mining Engineering*, 64(3):45–49.

Bicchi, A., Bavaro, M., Boccadamo, G., De Carli, D., Filippini, R., Grioli, G., Piccigallo, M., Rosi, A., Schiavi, R., Sen, S., et al. (2008). Physical human-robot interaction: Dependability, safety, and performance. In *2008 10th IEEE International Workshop on Advanced Motion Control*, pages 9–14. IEEE.

Billingsley, J. and Brett, P. (2015). *Machine Vision and Mechatronics in Practice*. Springer Berlin Heidelberg.

Blevins, T. (2012). Pid advances in industrial control. In *Preprints IFAC Conference on Advances in PID Control*. Citeseer.

Bonchis, A., Duff, E., Roberts, J., and Bosse, M. (2013). Robotic explosive charging in mining and construction applications. *IEEE Transactions on Automation Science and Engineering*, 11(1):245–250.

Boulter, A. and Hall, R. (2015). Wireless network requirements for the successful implementation of automation and other innovative technologies in open-pit mining. *International Journal of Mining, Reclamation and Environment*, 29(5):368–379.

Butler, J. T. and Agah, A. (2001). Psychological effects of behavior patterns of a mobile personal robot. *Autonomous Robots*, 10(2):185–202.

Cirillo, A., Cirillo, P., De Maria, G., Natale, C., and Pirozzi, S. (2013). A proximity/contact-force sensor for human safety in industrial robot environment. In *2013 IEEE/ASME International Conference on Advanced Intelligent Mechatronics*, pages 1272–1277. IEEE.

Colgate, E., Bicchi, A., Peshkin, M. A., and Colgate, J. E. (2008). Safety for physical human-robot interaction. In *Springer handbook of robotics*, pages 1335–1348. Springer.

Dadhich, S., Bodin, U., and Andersson, U. (2016). Key challenges in automation of earth-moving machines. *Automation in Construction*, 68:212–222.

Djuric, A. M., Urbanic, R., and Rickli, J. (2016). A framework for collaborative robot (cobot) integration in advanced manufacturing systems. *SAE International Journal of Materials and Manufacturing*, 9(2):457–464.

Ducarme, J., Kwitowski, A., and Bartels, J. (2010). Operating speed assessments of underground mining equipment. *Mining Engineering*, 62(3):39.

Etschberger, K. (2001). Controller area network-basics. *Protocols, Chips and Applications Controller Area Network-Basics, Protocols, Chips and Application, IXXAT Automation.*

Fan, Q., Li, W., Hui, J., Wu, L., Yu, Z., Yan, W., and Zhou, L. (2014). Integrated positioning for coal mining machinery in enclosed underground mine based on sins/wsn. *The Scientific World Journal*, 2014.

Farry, K. A., Walker, I. D., and Baraniuk, R. G. (1996). Myoelectric teleoperation of a complex robotic hand. *IEEE Transactions on Robotics and Automation*, 12(5):775–788.

Fei, Y.-n. and Wu, Q.-h. (2006). Tracking control of robot manipulators via output feedback linearization. *Frontiers of Mechanical Engineering in China*, 1(3):329–335.

Ferrara, A., Incremona, G. P., and Cucuzzella, M. (2019). *Advanced and optimization based sliding mode control: Theory and applications*. SIAM.

Ferreira, P. and Minova, R. (2012). A perspective on underground support technologies in southern african platinum mines to reduce safety risks and enhance productivity. In *Proceedings of the Southern African Institute of Mining and Metallurgy Platinum Conference*, pages 445–482. Sun City.

Foley, M. W., Julien, R. H., and Copeland, B. R. (2005). A comparison of pid controller tuning methods. *The Canadian Journal of Chemical Engineering*, 83(4):712–722.

Grehl, S., Donner, M., Ferber, M., Dietze, A., Mischo, H., and Jung, B. (2015). Mining-rox–mobile robots in underground mining. In *Third International Future Mining Conference*, pages 57–64.

Grehl, S., Mischo, H., Jung, B., et al. (2017). Research perspective-mobile robots in underground mining. *AusIMM Bulletin*, (Feb 2017):44.

Guiochet, J. (2016). Hazard analysis of human–robot interactions with hazop–uml. *Safety science*, 84:225–237.

Güth, F., Wolf, F., Grehl, S., Lösch, R., Varga, S., Rezaei, N., Mischo, H., Jung, B., Benndorf, J., Rehkopf, A., et al. (2018). Autonomous robots and the internet of things in underground mining. In *Conference on Smart Systems Integration, no. April, Dresden*, pages 215–222.

Hattingh, T. and Keys, O. (2010). How applicable is industrial engineering in mining. In *The 4th International Platinum Conference, Platinum in Transition 'Boom or Bust', The Southern African Institute of Mining and Metallurgy*, pages 205–210.

Helander, M. G., Krohn, G. S., and Curtin, R. (1983). Safety of roof-bolting operations in underground coal mines. *Journal of Occupational Accidents*, 5(3):161–175.

Herrero, D., Villagrá, J., and Martínez, H. (2013). Self-configuration of waypoints for docking maneuvers of flexible automated guided vehicles. *IEEE Transactions on Automation Science and Engineering*, 10(2):470–475.

Houshangi, N. and Azizi, F. (2006). Mobile robot position determination using data integration of odometry and gyroscope. In *2006 World Automation Congress*, pages 1–8. Proceedings of the Canadian Conference on Electrical and Computer Engineering, Ontario, Canada 2004.

Huh, S., Lee, U., Shim, H., Park, J.-B., and Noh, J.-H. (2011). Development of an unmanned coal mining robot and a tele-operation system. In *2011 11th International Conference on Control, Automation and Systems, Gyeonggi-do, South Korea*, pages 31–35. IEEE.

Iqbal, J., Khan, H., Tsagarakis, N. G., and Caldwell, D. G. (2014). A novel exoskeleton robotic system for hand rehabilitation–conceptualization to prototyping. *Biocybernetics and biomedical engineering*, 34(2):79–89.

Jackson, S., Hitchins, D., and Eisner, H. (2010). What is the systems approach? *Insight*, 13(1):41–43.

Javdani, S., Admoni, H., Pellegrinelli, S., Srinivasa, S. S., and Bagnell, J. A. (2018). Shared autonomy via hindsight optimization for teleoperation and teaming. *The International Journal of Robotics Research*, 37(7):717–742.

Jobes, C. C. (1990). Applied automation for the proposed automated roof reinforcement installation system. *U. S. Bureau of Mines - Electrical Electronic Systems*, Internal Report 4799(1):2–4.

Krüger, J., Lien, T. K., and Verl, A. (2009). Cooperation of human and machines in assembly lines. *CIRP annals*, 58(2):628–646.

KUKA (2016). Kuka lbr iiwa 14 r820. `http://www.kuka-robotics.com/en/products/industrial_robots/sensitiv/lbr_iiwa_14_r820/start.htm`.

Larsson, J., Broxvall, M., and Saffiotti, A. (2006). A navigation system for automated loaders in underground mines. In *Field and Service Robotics*, pages 129–140. New York, NY: IEEE.

Lasota, P. A., Fong, T., Shah, J. A., et al. (2017). *A survey of methods for safe human-robot interaction*. Now Publishers.

Leitner, J. (2009). Multi-robot cooperation in space: A survey. In *2009 Advanced Technologies for Enhanced Quality of Life*, pages 144–151. IEEE.

Li, M., Imou, K., Wakabayashi, K., and Yokoyama, S. (2009). Review of research on agricultural vehicle autonomous guidance. *International Journal of Agricultural and Biological Engineering*, 2(3):1–16.

Li, Y., Zhang, Q., and Zhang, W. (2017). Design of mine locomotive system based on can bus. In *MATEC Web of Conferences*, volume 139, page 00187. EDP Sciences.

Lindmark, D. M. and Servin, M. (2018). Computational exploration of robotic rock loading. *Robotics and Autonomous Systems*, 106:117–129.

Listak, J. and Beck, T. (2012). Development of a canopy. *Mining Engineering*, 64(7):72–79.

Lösch, R., Grehl, S., Donner, M., Buhl, C., and Jung, B. (2018). Design of an autonomous robot for mapping, navigation, and manipulation in underground mines. In *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pages 1407–1412. IEEE.

Lowe, M. J., Peterson, J. S., Yantek, D. S., Alcorn, L. A., and Michael, R. (2010). A control suite to reduce roof bolting machine drilling noise. In *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*, volume 2010, pages 1373–1384. Institute of Noise Control Engineering.

Lu, T.-F. (2009). Bucket wheel reclaimer modeling as a robotic arm. In *2009 IEEE International Conference on Robotics and Biomimetics (ROBIO)*, pages 263–268. IEEE.

Lynas, D. and Horberry, T. (2011). Human factor issues with automated mining equipment. *The Ergonomics Open Journal*, 4(1).

Marshall, J., Barfoot, T., and Larsson, J. (2008). Autonomous underground tramming for center-articulated vehicles. *Journal of Field Robotics*, 25(6-7):400–421.

Marshall, J. A., Bonchis, A., Nebot, E., and Scheding, S. (2016). Robotics in mining. In *Springer handbook of robotics*, pages 1549–1576. Springer.

Michael, R., Yantek, D., Johnson, D., Ferro, E., and Swope, C. (2011). Development of elastomeric isolators to reduce roof bolting machine drilling noise. *Noise control engineering journal*, 59(6):591–612.

Michael, R., Yantek, D., Johnson, D., Ferro, E., and Swope, C. (2015). Development of elastomeric isolators to reduce roof bolting machine drilling noise. *Noise control engineering journal*, 59:591–612.

Miller, W. K. and McLellan, R. R. (1975). Analysis of disabling injuries related to roof bolting in underground bituminous coal mines. Technical report, Mining Enforcement and Safety Administration, Denver, CO (USA). Health and Safety Analysis Center.

Modares, H., Ranatunga, I., Lewis, F. L., and Popa, D. O. (2015). Optimized assistive human–robot interaction using reinforcement learning. *IEEE transactions on cybernetics*, 46(3):655–667.

Moulières-Seban, T., Bitonneau, D., Salotti, J.-M., Thibault, J.-F., and Claverie, B. (2017). Human factors issues for the design of a cobotic system. In *Advances in human factors in robots and unmanned systems*, pages 375–385. Springer.

Müller, R., Vette, M., and Mailahn, O. (2016). Process-oriented task assignment for assembly processes with human-robot interaction. *Procedia CIRP*, 44:210–215.

Mumm, J. and Mutlu, B. (2011). Human-robot proxemics: physical and psychological distancing in human-robot interaction. In *Proceedings of the 6th international conference on Human-robot interaction*, pages 331–338.

Nagaraj, B. and Murugananth, N. (2010). A comparative study of pid controller tuning using ga, ep, pso and aco. In *2010 International Conference On Communication Control And Computing Technologies*, pages 305–313. IEEE.

Nguyen-Tuong, D., Seeger, M., and Peters, J. (2008). Computed torque control with nonparametric regression models. In *2008 American Control Conference*, pages 212–217.

Nikolaidis, S., Zhu, Y. X., Hsu, D., and Srinivasa, S. (2017). Human-robot mutual adaptation in shared autonomy. In *2017 12th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*, pages 294–302. IEEE.

Olmedo, N. A., Fisseha, B., Wilson, W., Barczyk, M., Zhang, H., and Lipsett, M. G. (2020). An automated vane shear test tool for environmental monitoring with unmanned ground vehicles. *Journal of Terramechanics*, 91:53–63.

Parker-Hannifin, C. (2016a). Iqan-lc5-c0x instruction book. `https://www.gsglobalresources.com/uploads/iqan-lc5-C0x_uk_user_manual.pdf`.

Parker-Hannifin, C. (2016b). Iqan-xa2 instruction book. `https://www.parker.com/Literature/Electronic/20Controls/20Division/Literature/20files/iqan-xa2_instruction_book.pdf`.

Parker-Hannifin, C. (2018). Iqan-md4 instruction book. `https://www.parker.com/Literature/Electronic/20Controls/20Division/Literature/20files/IQAN-MD4_instructionbook_UK.pdf`.

Passenberg, C., Groten, R., Peer, A., and Buss, M. (2011). Towards real-time haptic assistance adaptation optimizing task performance and human effort. In *2011 IEEE World Haptics Conference*, pages 155–160. IEEE.

Pedersen, M. R., Høilund, C., and Krüger, V. (2012). Using human gestures and generic skills to instruct a mobile robot arm in a feeder filling scenario. In *2012 IEEE International Conference on Mechatronics and Automation*, pages 243–248. IEEE.

Pedrocchi, N., Vicentini, F., Matteo, M., and Tosatti, L. M. (2013). Safe human-robot cooperation in an industrial environment. *International Journal of Advanced Robotic Systems*, 10(1):27.

Peng, S. S., Du, F., Cheng, J., and Li, Y. (2019). Automation in us longwall coal mining: A state-of-the-art review. *International Journal of Mining Science and Technology*, 29(2):151–159.

Peshkin, M. and Colgate, E. (1999). Cobots. *Industrial Robot: An International Journal*, 26(5):335–341.

Pfeiffer, O., Ayre, A., and Keydel, C. (2008). *Embedded networking with CAN and CANopen*. Copperhill Media.

Piltan, F., Yarmahmoudi, M., Shamsodini, M., Mazlomian, E., and Hosainpour, A. (2012). Puma-560 robot manipulator position computed torque control methods using matlab/simulink and their integration into graduate nonlinear control and matlab courses. *International Journal of Robotics and Automation*, 3:167–191.

Plotnikov, N., Kolokoltseva, E., and Volkova, Y. (2020). Technical review of robotic complexes for underground mining. In *IOP Conference Series: Earth and Environmental Science*, volume 459, page 042025. Institute of Physics Publishing (IOP).

Pollock, D., Potts, J. D., and Joy, G. (2009). Investigation into dust exposures and mining practices in mines in the southern appalachian region. *Society for Mining, Metallurgy, and Exploration, Incorporated*, 62(2):44–49.

Polotski, V. and Hemami, A. (1997). Control of articulated vehicle for mining applications: Modeling and laboratory experiments. In *Proceedings of the 1997 IEEE International Conference on Control Applications*, pages 318–323. IEEE.

Rahimi, E., Shekarian, Y., and Roghanchi, P. (2021). An analysis of coal mine lung diseases in the us coal mines. In *Mine Ventilation*, pages 218–224. CRC Press.

Rakita, D., Mutlu, B., Gleicher, M., and Hiatt, L. M. (2019). Shared control–based bimanual robot manipulation. *Science Robotics*, 4(30).

Ralston, J., Reid, D., Hargrave, C., and Hainsworth, D. (2014). Sensing for advancing mining automation capability: A review of underground automation technology development. *International Journal of Mining Science and Technology*, 24(3):305–310.

Reed, W., Joy, G., Kendall, B., Bailey, A., and Zheng, Y. (2017). Development of a roof bolter canopy air curtain for respirable dust control. *Mining Engineering*, 69(1):33.

Reid, D., Ralston, J., Dunn, M., and Hargrave, C. (2011). A major step forward in continuous miner automation. In *11th Underground Coal Operators' Conference, University of Wollongong the Australasian Institute of Mining and Metallurgy*, pages 165–171.

Rizos, C., Lilly, B., Robertson, C., and Gambale, N. (2011). Open cut mine machinery automation: Going beyond gnss with locata. In *Proc. 2nd Int. Future Mining Conf., Sydney, Australia*, pages 22–23.

Roberts, J. M., Duff, E. S., and Corke, P. I. (2002). Reactive navigation and opportunistic localization for autonomous underground mining vehicles. *Information Sciences*, 145(1-2):127–146.

Robotics, R. (2015). Sawyer, the high performance collaborative robot. http://www.rethinkrobotics.com/sawyer-intera-3/,2015b.

Robots, G. (2015). Intera v3.2 is available for baxter robot. https://www.generationrobots.com/blog/en/intera-v3-2-is-available-for-baxter-robot/.

Rosenthal, S. and Veloso, M. (2021). Mobile robot planning to seek help with spatially-situated tasks. *Proceedings of the AAAI Conference on Artificial Intelligence*, 26(1):2067–2073.

Ruiz, M. (2009). *Optimization of a strapdown inertial navigation system*. MSc Thesis, University of Texas, El Paso.

Safeea, M., Neto, P., and Bearee, R. (2019). On-line collision avoidance for collaborative robot manipulators by adjusting off-line generated paths: An industrial use case. *Robotics and Autonomous Systems*, 119:278–288.

Salisbury, K., Townsend, W., Ebrman, B., and DiPietro, D. (1988). Preliminary design of a whole-arm manipulation system (wams). In *Proceedings. 1988 IEEE International Conference on Robotics and Automation*, pages 254–260. IEEE.

Scheding, S., Dissanayake, G., Nebot, E. M., and Durrant-Whyte, H. (1999). An experiment in autonomous navigation of an underground mining vehicle. *IEEE Transactions on robotics and Automation*, 15(1):85–95.

Schnakenberg, G. (1997). Progress toward a reduced exposure mining system. *Mining Engineering*, 49(2):73–77.

Sisbot, E. A., Marin-Urias, L. F., Alami, R., and Simeon, T. (2007). A human aware mobile robot motion planner. *IEEE Transactions on Robotics*, 23(5):874–883.

Thrybom, L., Neander, J., Hansen, E., and Landernas, K. (2015). Future challenges of positioning in underground mines. *IFAC-PapersOnLine*, 48(10):222–226.

Tyuleneva, T., Kabanov, E., Moldazhanov, M., and Plotnikov, E. (2021). Improving the professional risk management system for methane and coal dust explosions using a risk-based approach. In *E3S Web of Conferences*, volume 278, pages 1027–1028. EDP Sciences.

Ullah, M. I., Ajwad, S. A., Islam, R. U., Iqbal, U., and Iqbal, J. (2014). Modeling and computed torque control of a 6 degree of freedom robotic arm. In *2014 International Conference on Robotics and Emerging Allied Technologies in Engineering (iCREATE)*, pages 133–138. IEEE.

Vasic, M. and Billard, A. (2013). Safety issues in human-robot interactions. In *2013 IEEE international conference on robotics and automation*, pages 197–204. IEEE.

Vaughan, B., Han, J. G., Gilmartin, E., and Campbell, N. (2012). Designing and implementing a platform for collecting multi-modal data of human-robot interaction. *Acta Polytechnica Hungarica*, 9(1):7–17.

Veloso, M. M., Biswas, J., Coltin, B., and Rosenthal, S. (2015). Cobots: Robust symbiotic autonomous mobile service robots. In *IJCAI*, page 4423.

Walker, S. (2012). Underground mining technology: Safer working conditions and higher productivity. *Engineering and Mining Journal*, page 6.

Wang, S. and Wang, S. (2020). Improving the shearer positioning accuracy using the shearer motion constraints in longwall panels. *IEEE Access*, 8:52466–52474.

Wang, X., X. J. . L. S. (2022). System overall design. in virtual reality technology in mining machinery. pages 15–34. Springer.

Wilkinson, N. (2004). Cooperative control in tele-operated mining environments. In *Proceedings of the UBC Human Interface Technology Conference, Vancouver, BC Canada*, pages 6–7.

Wynn, R. B., Huvenne, V. A., Le Bas, T. P., Murton, B. J., Connelly, D. P., Bett, B. J., Ruhl, H. A., Morris, K. J., Peakall, J., Parsons, D. R., et al. (2014). Autonomous underwater vehicles (auvs): Their past, present and future contributions to the advancement of marine geoscience. *Marine Geology*, 352:451–468.

Xu, Z.-p. and Wang, Z.-b. (2010). Research on the key technology of shearer position. In *2010 International Conference on Intelligent System Design and Engineering Application*, volume 2, pages 280–283. IEEE.

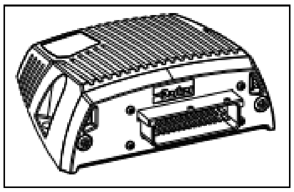
Zhang, J., Wang, F.-Y., Wang, K., Lin, W.-H., Xu, X., and Chen, C. (2011). Data-driven intelligent transportation systems: A survey. *IEEE Transactions on Intelligent Transportation Systems*, 12(4):1624–1639.

Zhou, J. (1995). Experimental evaluations of a kinematic compensation control method for hydraulic robot manipulators. *Control Engineering Practice*, 3(5):675–684.

Appendix A: iQAN Modules

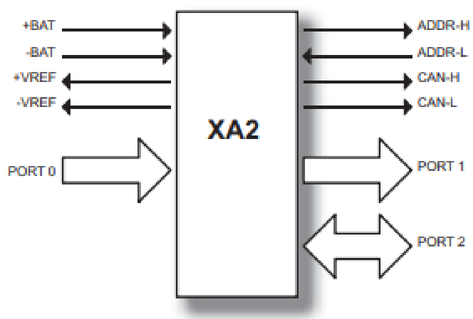
IQAN-XA2

The IQAN-XA2 is a flexible expansion module designed for controlling hydraulic systems in vehicles and machinery, using 12/24 Vdc power supply.



The IQAN-XA2 module.

I/O overview



Inputs

The IQAN-XA2 module has eight (8) *voltage inputs* VIN-A thru VIN-H for connection of 0-5 Vdc signals. The inputs VIN-E thru VIN-H are multi-purpose and for flexibility may be configured in other ways. The two input pins VIN-E and VIN-G can be configured as *frequency inputs* for measuring frequency. The group of four pins VIN-E thru VIN-H can be configured as *quadrature* or *directional inputs* for measuring directional frequency. *Voltage inputs, frequency inputs, quadrature inputs* and *directional inputs* share positions, see below.

(8) Voltage inputs VIN-A, VIN-B, VIN-C, VIN-D.....VIN-H

or

(6) Voltage inputs VIN-A thru VIN-D,VIN-F and VIN-H.
(2) Frequency inputs FIN-A and FIN-B use positions VIN-E and VIN-G.

or

(4) Voltage inputs VIN-A thru VIN-D. (2) Quadrature or Directional inputs DFIN-A+/DFIN-A- and DFIN-B+/DFIN-B- use positions VIN-E thru VIN-H.

or

(8) Digital inputs DIN-A, DIN-B.....DIN-H use positions VIN-A thru VIN-H.

Figure A1: Figure retrieved from Parker-Hannifin (2016b)

Proportional outputs

The XA2 module has six (6) double *proportional outputs* for controlling proportional valves. These outputs can control six bi-directional valve sections or six single solenoid devices (ie. proportional cartridge valves). The proportional outputs can be used in two different modes. Either *Current mode* or *PWM mode* signals can be selected and the parameters configured using IQAN software.

In both modes, the output applies battery voltage minus voltage drop during the on-phase. The difference between COUT and PWMOUT is that for COUT there is closed loop control of current, and for PWMOUT there is open control of current by commanding a *modulation ratio* (MR%).

For flexibility these outputs may also be configured as up to six (6) *on/off outputs* and up to twelve (12) *on/off intputs*. The proportional outputs, on/off outputs and on/off inputs share positions, see below.

(6) double proportional outputs COUT-A thru COUT-F

or

(6) on/off outputs DOUT-G thru DOUT-L, each pair of return pins may then be used as (2) on/off inputs, (12) total, DIN-I thru DIN-T.

In order to increase the performance of proportional outputs when controlling proportional valves, the *dither frequency* can be adjusted.

High power On/Off outputs

The XA2 module has six (6) *on/off outputs* that are high-side power outputs. These outputs may not be configured as proportional, see below.

(6) On/off outputs DOUT-A thru DOUT-F

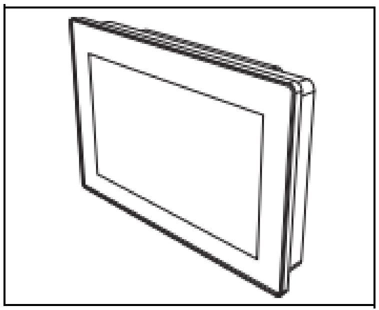
CAN related functions

The master uses the CAN-bus (CAN = Controller Area Network) to communicate with the modules. The CAN-bus is a robust communication protocol that is widely used and well proven within the automotive industry.

Figure A2: Figure retrieved from Parker-Hannifin (2016b)

IQAN-MD4

The IQAN-MD4 is a family of combined display and bus master modules capable of running applications created by IQANdesign software. Built on a 32-bit platform the units have large computational power and is capable of controlling large applications.

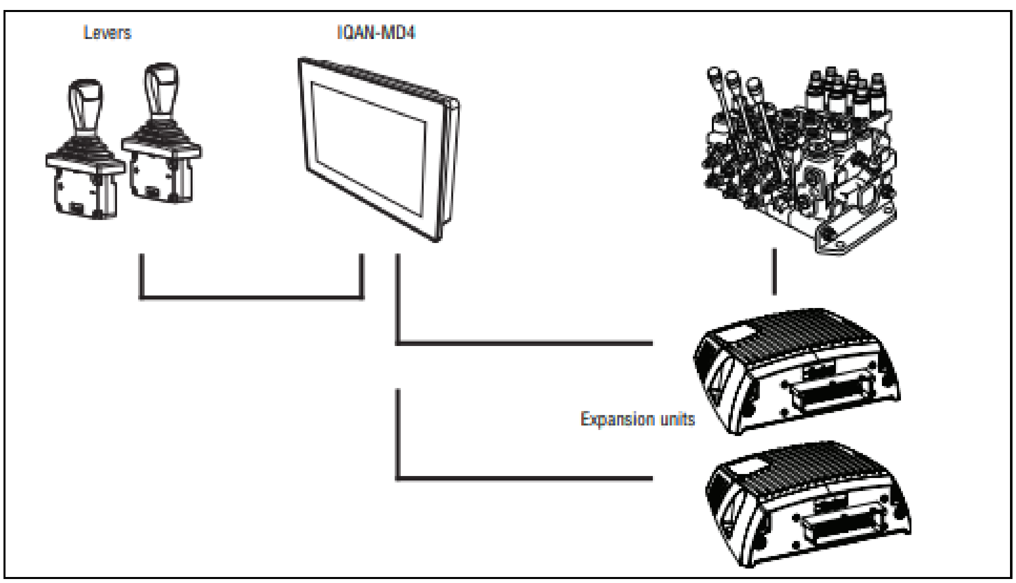


The IQAN-MD4 module.

System overview

The master module, IQAN-MD4, is the central unit in the system, or in the case of a multi-master system, one of the central units. IQAN-MD4 has four CAN buses and two ethernet ports. The CAN buses support ICP and are able to control IQAN expansion units. SAE J1939 and Generic CAN protocols are also supported on the CAN buses and gives the possibility to interface to 3rd party units.

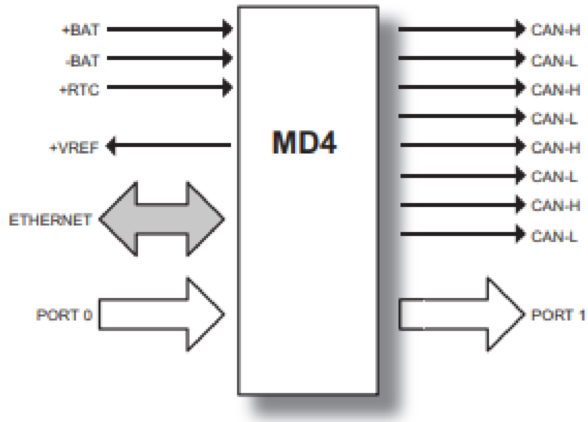
A touch screen in combination with a graphical display makes system feedback with user interaction possible. The display in the module has very high optical performance across a wide operating temperature range and over a wide range of ambient light.
IQAN-MD4 has voltage and digital inputs that are designed to be flexibly configured using IQANdesign software. The unit also has four low side digital outputs. All I/O are EMI filtered and protected against short circuit to -BAT and +BAT.



A typical IQAN-MD4 System

Figure A3: Figure retrieved from Parker-Hannifin (2018)

I/O



Voltage inputs

The IQAN-MD4 module has two (2) voltage inputs VIN-A andVIN-B for connection of 0-5 Vdc signals. These inputs can be configured as digital inputs for reading switches. Voltage inputs and digital inputs share positions, see below.

(2) Voltage inputs VIN-A and VIN-B
or
(2) Digital inputs DIN-I and DIN-J

Digital inputs

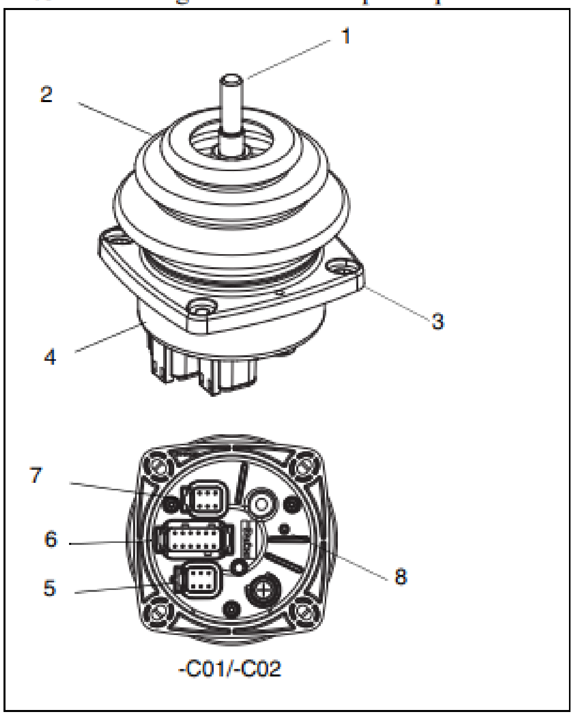
The IQAN-MD4 module has eight (8) digital inputs DIN-A thru DIN-H. DIN-A thru DIN-D are multi purpose and can be configured as low-side *on/off outputs*. DIN-G and DIN-H are multi purpose and can be configured as a *directional pulse count input*. see below.

(8) Digital inputs DIN-A thru DIN-H
or
(4) Digital inputs DIN-E thru DIN-H, (4) Digital outputs DOUT-A thru DOUT-D
or
(6) Digital inputs DIN-A thru DIN-F, (1) Directional pulse count input DPCNT

Figure A4: Figure retrieved from Parker-Hannifin (2018)

IQAN-LC5-C0x

The CAN joystick replaces IQAN-LL (fourth generation) coordinate levers and therefore is called IQAN-LC5 (**L**ever, **C**oordinate **5**th generation). The designation -C01 (**C**ANbus, type **01**) represents the CAN version. The joystick version -C02-U2 is configured to be a drop-in replacement for the IQAN-LL-2U. The joystick version -C03-G is configured to be a drop-in replacement for the IQAN-LL-3G



The IQAN-LC5-C0x parts

The control lever's parts

Control lever -LC5-C0x consists of:

1 Stem, -U2 shown, no handle mounted, (-H1 ball knob, will fit to stem).

2 Bellows, -U2 shown, no handle mounted, (other bellows for -H1 ball knob).

3 Mounting flange.

4 Lower enclosure.

5 Connector C1 for CAN bus, supply voltage, address idTag (-C01, -C02, -C03).

6 Connector C2 for inputs and outputs (-C01, -C02, -C03).

7 Connector C3 for inputs and outputs (-C01, -C02, -C03).

8 Indicator for supply voltage and status (-C01, -C02, -C03).

Figure A5: Figure retrieved from Parker-Hannifin (2016a)

The IQAN-LC5-C0x control signals

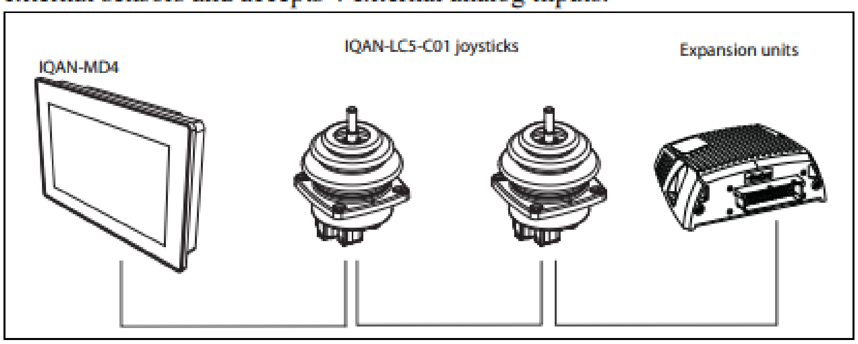
The IQAN-LC5-C0x is used to control the object in two directions:

- the lever is moved to the right/left, direction X +/-.
- the lever is moved forward/back, direction Y +/-.

The control signal is proportional to the lever's working range.

The control signal is transferred internally from the IQAN-LC5-C0x via the CAN bus to the IQAN master unit. The control signal's data is treated in the system and is then available as an output signal, for example in the expansion unit IQAN-XA2.

The IQAN-LC5-C01 has three Deutsch DTM connectors built into its base. Connector C1 is a 6 position connector for power, CAN and addressing of the joystick. Connector C2 is a 12 position connector for internal and external analog or digital signals, which may come from the handle of the joystick, or from other input devices in an armrest or panel. Connector C3 is an additional 6 position connector that will provide VREF for external sensors and accepts 4 external analog inputs.



IQAN-LC5-C01 in a typical system

I/O overview -C01

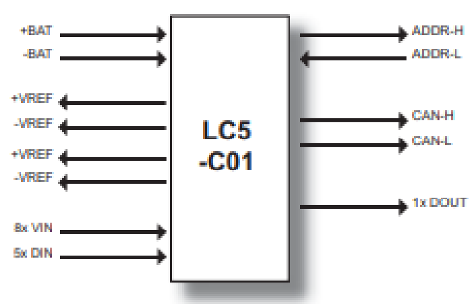


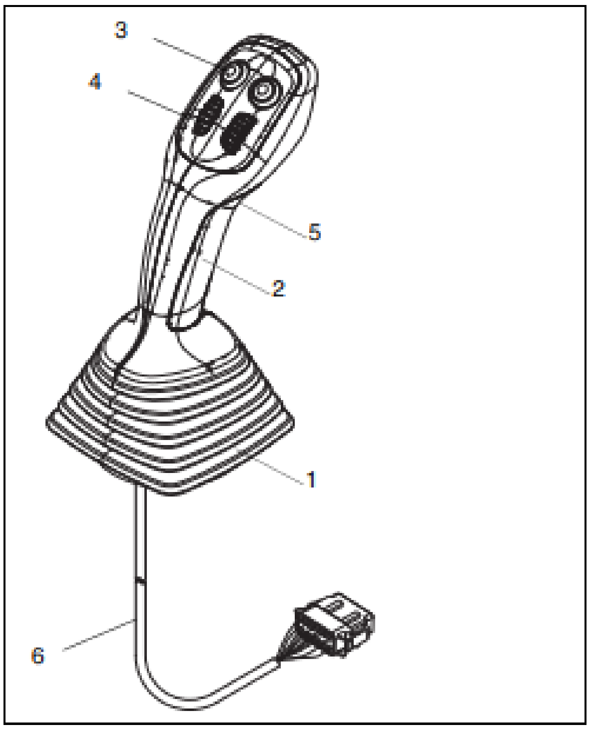
Figure A6: Figure retrieved from Parker-Hannifin (2016a)

MP handle

The IQAN-LC5-C01 is designed to be used with the Multi-Purpose (MP) handle. The MP handle together with a IQAN-LC5-C01 base will have one Deutsch DTM connector for interfacing to connector C2 or C3 in the joystick base.

In order to reduce operator fatigue, the MP handle incorporates a hand rest, and is designed for both left and right-handed use.

To extend operating life the housing is made of a corrosive-free material, and is specially adapted for moisture drainage to protect the the system electronics. The MP handle uses a bellow that can be quickly changed to simplify field replacement. The cable between base and handle is routed directly through the base plate, eliminating the risk of damage and simplifying field service, while the use of a single circuit board and Hall effect sensors minimise the number of components and moving parts.



The MP handle parts.

The handle's parts

MP handle consists of:

1 Bellows, -MP handle.

2 Handle, -MPB2W2T1 shown, (other configurations are possible).

3 Momentary buttons.

4 Proportional thumbwheel (-MP handle thumbwheel has dual, mirrored outputs).

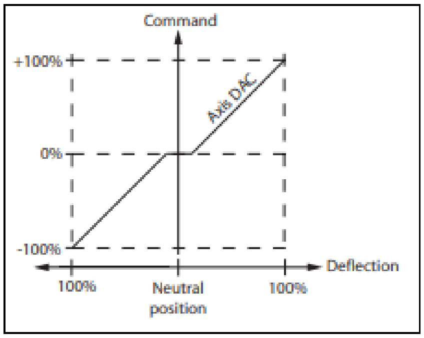
5 Momentary trigger button.

6 Cable and connector for -MP (6 pos. or 12 pos., depending on handle functions connected to the base).

Figure A7: Figure retrieved from Parker-Hannifin (2016a)

Directional Analogue Channels (DAC)

The IQAN-LC5-C01 joystick has five (5) *directional analogue channels* for use in IQAN applications. These are assigned to X-axis, Y-axis and up to three additional proportional command signals denoted as Z1 thru Z3 (when the -MP handle is used). The DAC channels are sent to the master unit via CAN and defined using IQAN software.



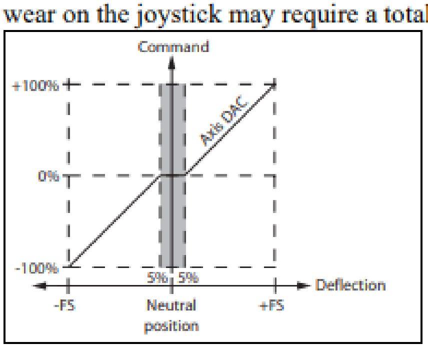
IQAN-LC5-C0x DAC channel

(2) Coordinate DAC outputs DAC-X and DAC-Y (internal, not in connectors)

(3) Auxiliary DAC outputs DAC-Z1 thru DAC-Z3 (external, via C2/C3 connectors)

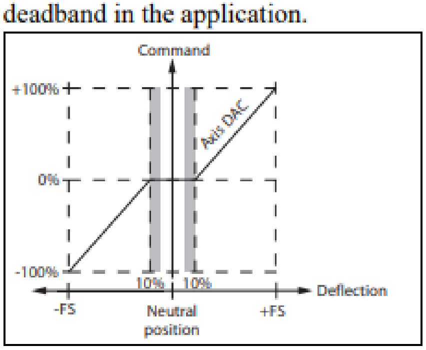
Joystick Deadband X, Y

The unit has a built in deadband of 5%. During the lifetime of the unit, the mechanical wear on the joystick may require a total deadband of 10%.



IQAN-LC5-C0x default deadband

To allow for wear over the life of the joystick, an additional 5 % should be added to the deadband in the application.

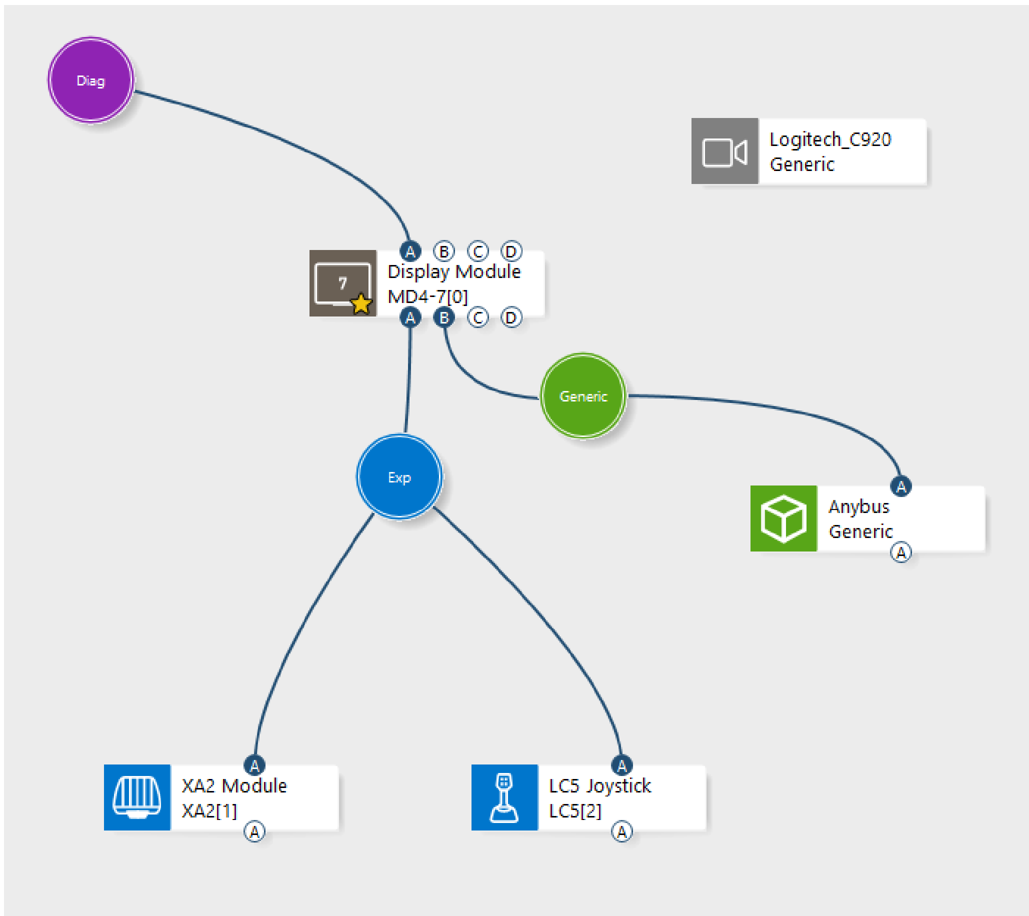


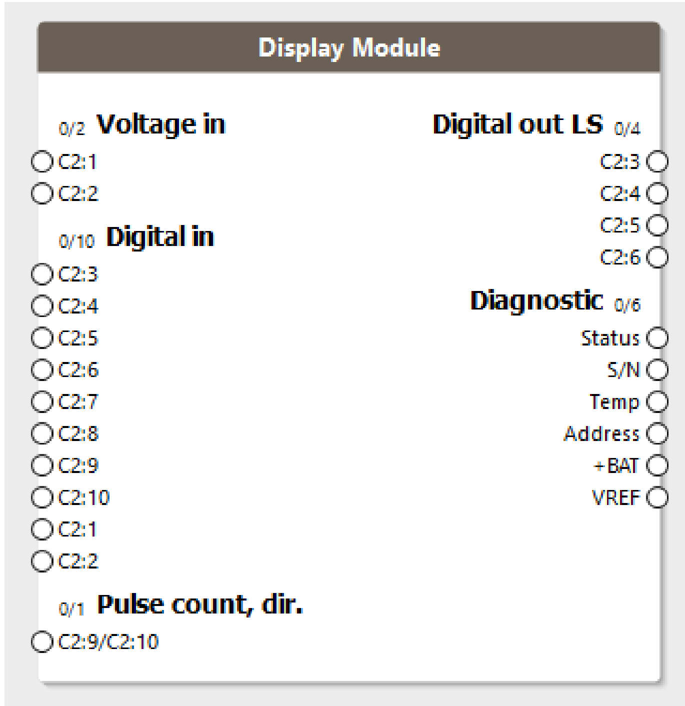
IQAN-LC5-C0x minimum recommended deadband

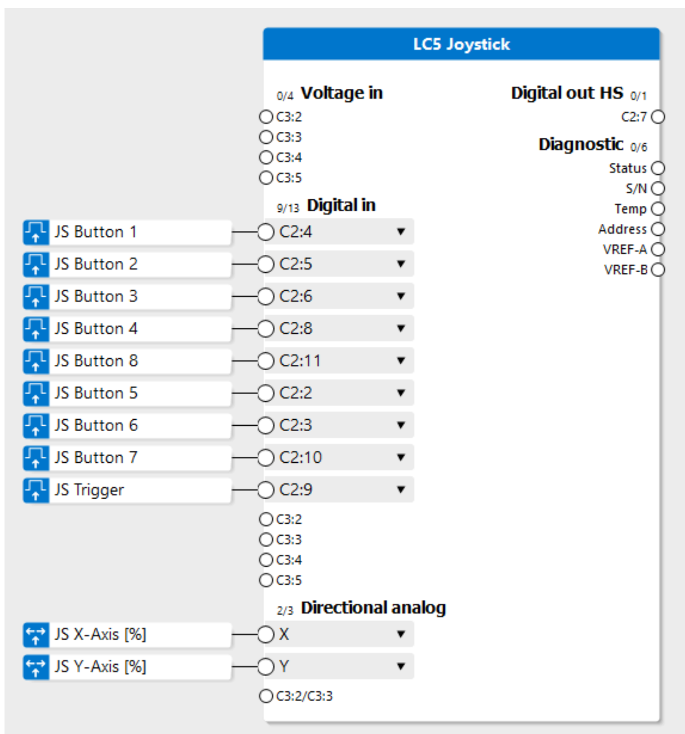
Figure A8: Figure retrieved from Parker-Hannifin (2016a)

Appendix B: IQANdesign (D6) Software Developed Logic

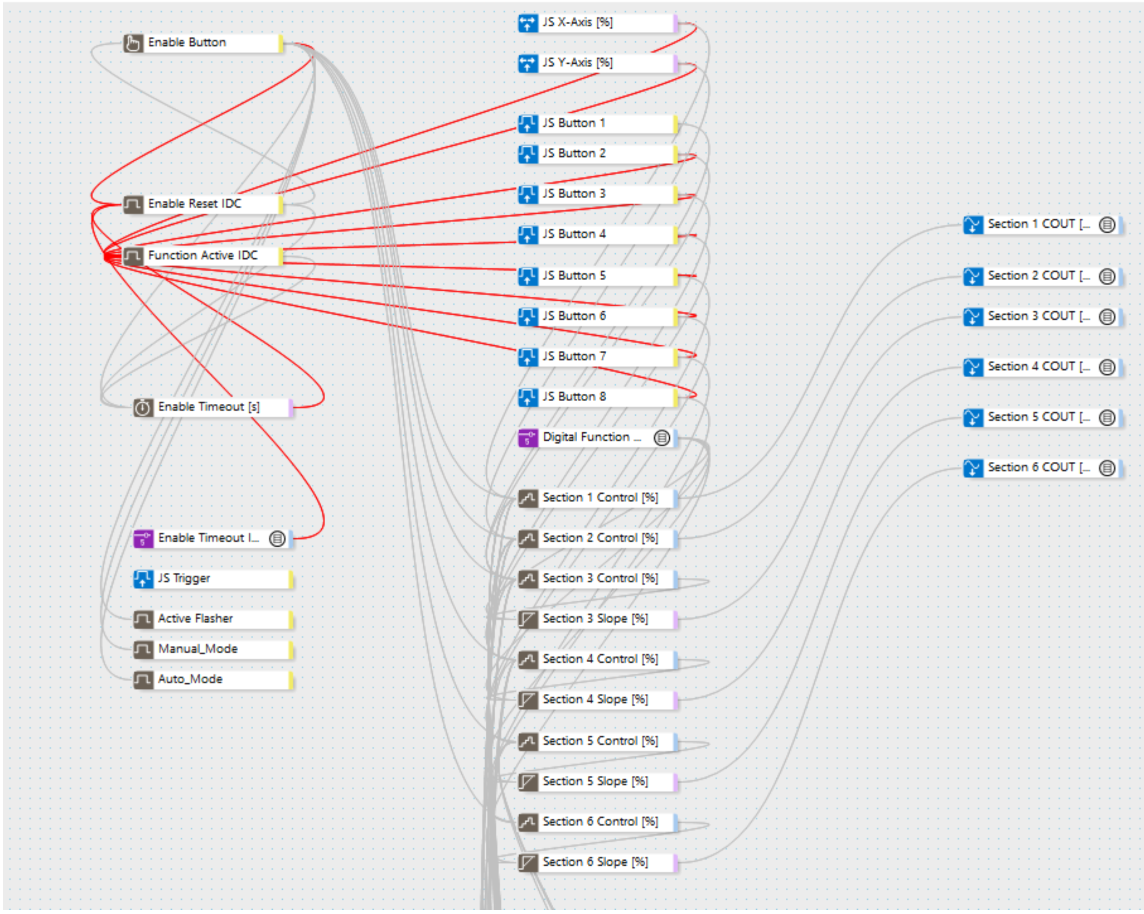
Modules

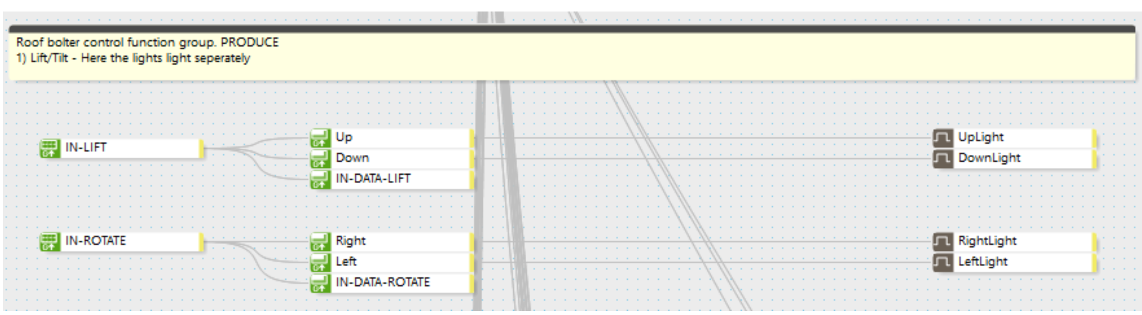


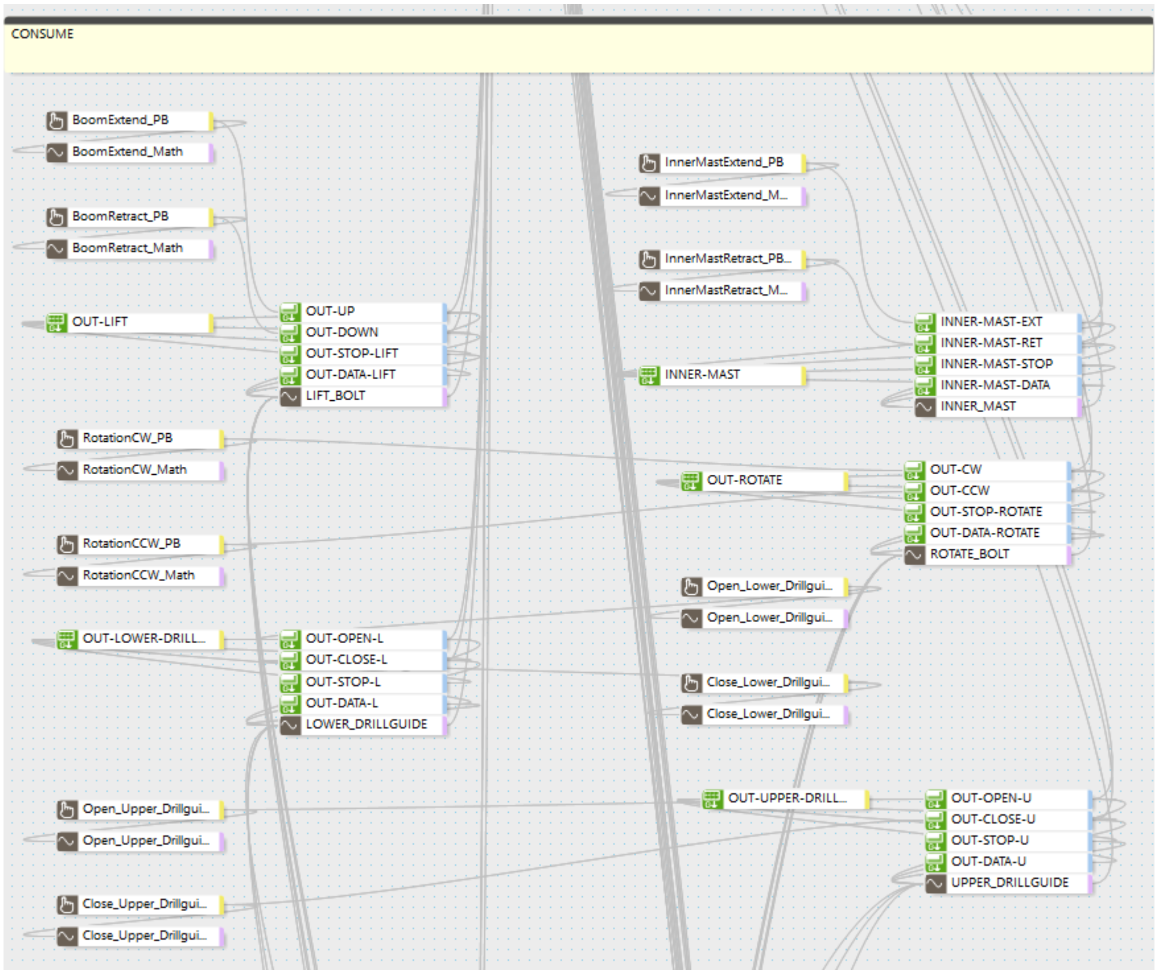

Display Module
0/2 Voltage in
C2:1
C2:2
0/10 Digital in
C2:3
C2:4
C2:5
C2:6
C2:7
C2:8
C2:9
C2:10
C2:1
C2:2
0/1 Pulse count, dir.
C2:9/C2:10
Digital out LS 0/4
C2:3
C2:4
C2:5
C2:6
Diagnostic 0/6
Status
S/N
Temp
Address
+BAT
VREF

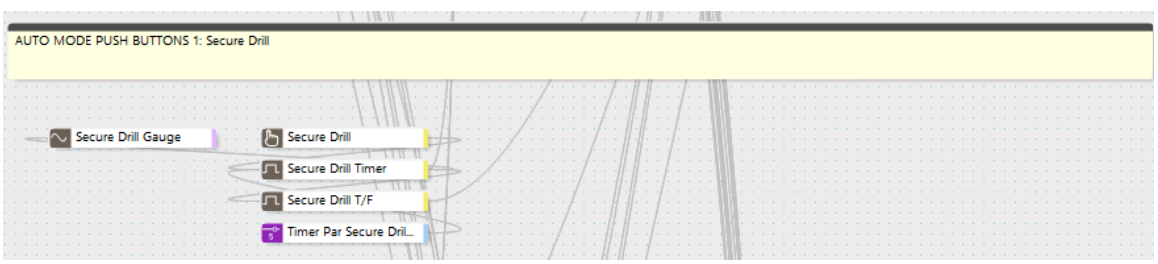

LC5 Joystick
0/4 Voltage in
C3:2
C3:3
C3:4
C3:5
9/13 Digital in
JS Button 1
C2:4
JS Button 2
C2:5
JS Button 3
C2:6
JS Button 4
C2:8
JS Button 8
C2:11
JS Button 5
C2:2
JS Button 6
C2:3
JS Button 7
C2:10
JS Trigger
C2:9
C3:2
C3:3
C3:4
C3:5
2/3 Directional analog
JS X-Axis [%]
X
JS Y-Axis [%]
Y
C3:2/C3:3
Digital out HS 0/1
C2:7
Diagnostic 0/6
Status
S/N
Temp
Address
VREF-A
VREF-B

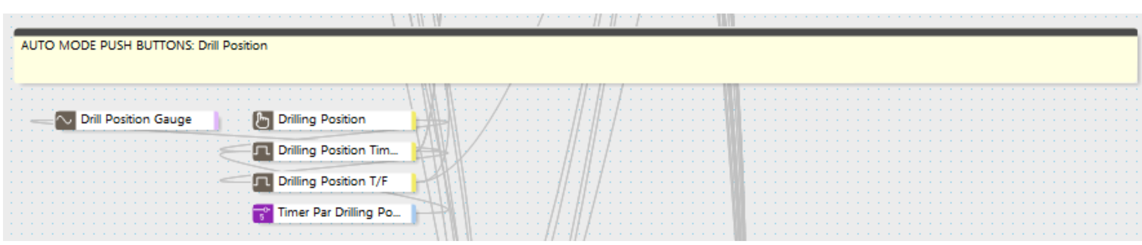
Application: Display Module application

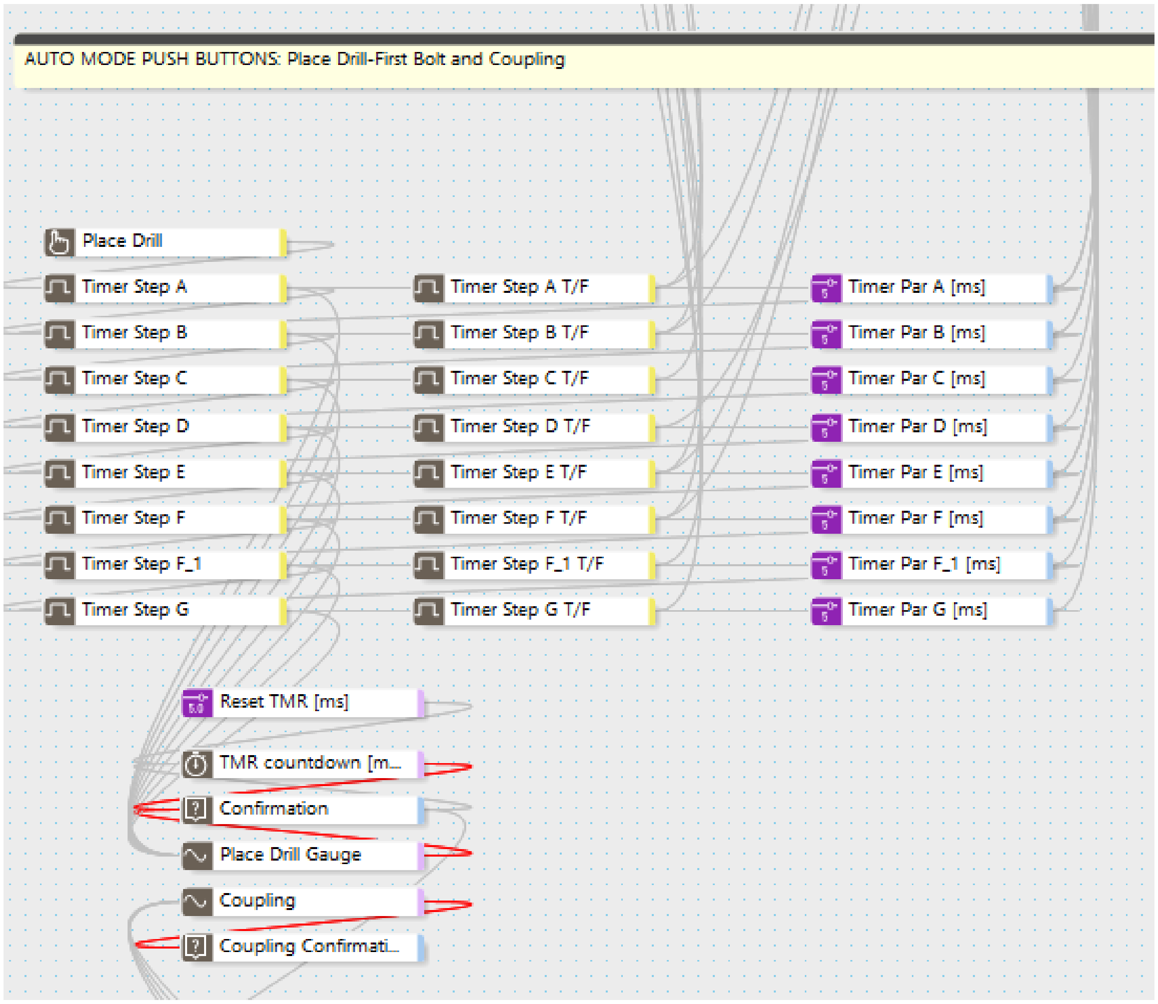


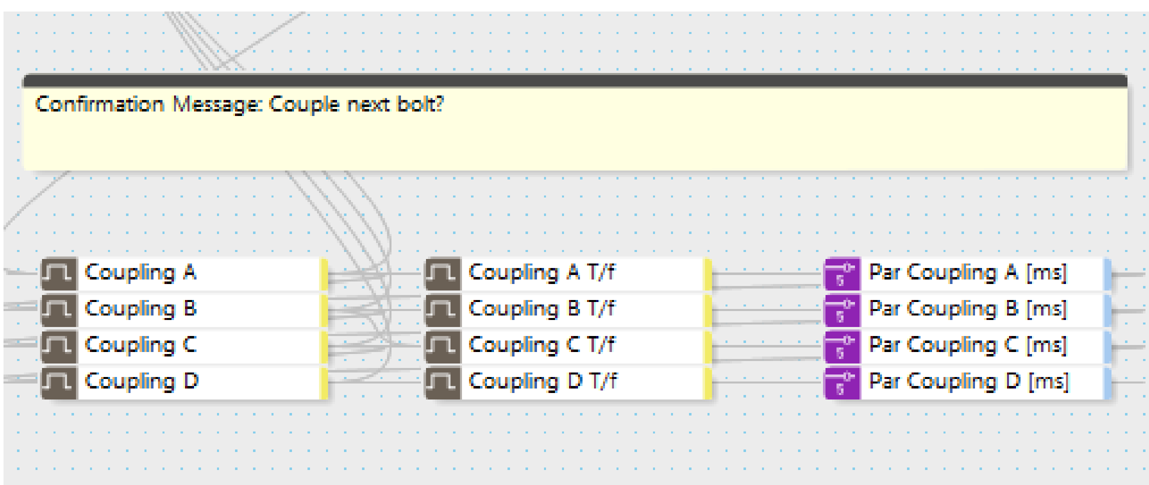



CONSUME
BoomExtend_PB
BoomExtend_Math
BoomRetract_PB
BoomRetract_Math
OUT-LIFT
OUT-UP
OUT-DOWN
OUT-STOP-LIFT
OUT-DATA-LIFT
LIFT_BOLT
RotationCW_PB
RotationCW_Math
RotationCCW_PB
RotationCCW_Math
OUT-LOWER-DRILL...
OUT-OPEN-L
OUT-CLOSE-L
OUT-STOP-L
OUT-DATA-L
LOWER_DRILLGUIDE
Open_Upper_Drillgui...
Open_Upper_Drillgui...
Close_Upper_Drillgui...
Close_Upper_Drillgui...
InnerMastExtend_PB
InnerMastExtend_M...
InnerMastRetract_PB...
InnerMastRetract_M...
INNER-MAST
INNER-MAST-EXT
INNER-MAST-RET
INNER-MAST-STOP
INNER-MAST-DATA
INNER_MAST
OUT-ROTATE
OUT-CW
OUT-CCW
OUT-STOP-ROTATE
OUT-DATA-ROTATE
ROTATE_BOLT
Open_Lower_Drillgui...
Open_Lower_Drillgui...
Close_Lower_Drillgui...
Close_Lower_Drillgui...
OUT-UPPER-DRILL...
OUT-OPEN-U
OUT-CLOSE-U
OUT-STOP-U
OUT-DATA-U
UPPER_DRILLGUIDE


AUTO MODE PUSH BUTTONS 1: Secure Drill
Secure Drill Gauge
Secure Drill
Secure Drill Timer
Secure Drill T/F
Timer Par Secure Dril...


AUTO MODE PUSH BUTTONS: Drill Position
Drill Position Gauge
Drilling Position
Drilling Position Tim...
Drilling Position T/F
Timer Par Drilling Po...


AUTO MODE PUSH BUTTONS: Place Drill-First Bolt and Coupling
Place Drill
Timer Step A
Timer Step B
Timer Step C
Timer Step D
Timer Step E
Timer Step F
Timer Step F_1
Timer Step G
Timer Step A T/F
Timer Step B T/F
Timer Step C T/F
Timer Step D T/F
Timer Step E T/F
Timer Step F T/F
Timer Step F_1 T/F
Timer Step G T/F
Timer Par A [ms]
Timer Par B [ms]
Timer Par C [ms]
Timer Par D [ms]
Timer Par E [ms]
Timer Par F [ms]
Timer Par F_1 [ms]
Timer Par G [ms]
Reset TMR [ms]
TMR countdown [m...
Confirmation
Place Drill Gauge
Coupling
Coupling Confirmati...


Confirmation Message: Couple next bolt?
Coupling A
Coupling B
Coupling C
Coupling D
Coupling A T/f
Coupling B T/f
Coupling C T/f
Coupling D T/f
Par Coupling A [ms]
Par Coupling B [ms]
Par Coupling C [ms]
Par Coupling D [ms]

Appendix C: Data Structure

All algorithms for statistical and spatial analysis as well as the algorithms for the estimation of missing values in data, were developed and run in *R* environment.

```
##################################################
#R packages used for the time series analysis
##################################################

library(ggplot)
library(ggplot2)
library(gstat)
library(imputeTS)
library(timeSeries)
library(xlsx)
library(readxl)

##################################################
#Import data from excel file
##################################################

RoofBolterExperiment <- read_excel("C:/Users/Owner/Desktop/
RoofBolterExperiment.xlsx")
View(RoofBolterExperiment)

Bolt1<-matrix(RoofBolterExperiment$
`1st Day-Insert Bolt (mm)`[1:8])
Bolt2<-matrix(RoofBolterExperiment$
`2nd Day-Insert Bolt (mm)`[1:8])
```

```
Coupling1<-matrix(RoofBolterExperiment$
`1st Day-Coupling Bolt (mm)`[1:8])
Coupling2<-matrix(RoofBolterExperiment$
`2nd Day-Coupling Bolt (mm)`[1:8])
EstimatedPosition<-matrix(RoofBolterExperiment$
`Original Position (mm)`[1:8])

##################################################
#Format data into time series
##################################################

TSBolt1<-ts(Bolt1,start=c(1, 1),end = c(8,1))
TSBolt2<-ts(Bolt2,start=c(1, 1),end = c(8,1))
TSCoupling1<-ts(Coupling1,start=c(1, 1),end = c(8,1))
TSCoupling2<- ts(Coupling2,start=c(1, 1),end = c(8,1))
TSStartPosition<-ts(EstimatedPosition,start=c(1, 1),end = c(8,1))

CompleteTS<-c(TSBolt1,TSBolt2,TSCoupling1,TSCoupling2)
CompleteEstimatedTS<-c(TSStartPosition,TSStartPosition,
TSStartPosition,TSStartPosition)
Original.data<-CompleteTS
Estimated.data<-CompleteEstimatedTS

##################################################
#Set graph size
##################################################

x11(width=8, height = 9, pointsize=15)
par(mfrow=c(1,1), mar=c(3,3,3,3))

##################################################
```

```
#Graph function groups
###################################################

make.scatter.function<-function(Original.data, Estimated.data)
{
  data<-data.frame(x=Original.data, y=Estimated.data)
  ggplot(data,aes(x,y))+geom_point()+theme_light()
    +xlab("Observed Vertical Distance (in)")
    +ylab("Estimated Vertical Distance (in)")
    +geom_smooth(method="lm",col="red")
    +theme(axis.title.y=element_text(size=14))
    +theme(axis.title.x = element_text(size=14))
    +theme(axis.text.x=element_text(size=14))
    +theme(axis.text.y=element_text(size=14))
}

make.hist.function<-function(Original.data, Estimated.data)
{
  p1<-hist(Original.data, breaks=30, col=alpha(rgb(0.9,0.1,0),
  0.7), xlab="",ylab="",main="", cex.lab=1.5,cex.axis=1.5)
  p2<-hist(Estimated.data, breaks=30, col=alpha(rgb(0,0,0.6),
  0.7),add=T,cex.lab=1.5,cex.axis=1.5)
  legend("topright",legend = c("Original","Estimated"),
         col=c(alpha(rgb(0.9,0.1,0),
         0.7), alpha(rgb(0,0,0.6),
         0.7)), pt.cex = 2, pch = 15, lwd = 3 )
}
```

Vita

Anastasia Xenaki

Education: Anastasia received the Engineering Diploma in Mineral Resources Engineering from the Technical University of Crete, Chania, Greece, in 2019. Her research interests include development and implementation of autonomous equipment/robotics in underground mining operations, and on the application of geostastistical methods and stochastic data analysis methods in mineral surveying applications.

Academic Employment: Research Assistant to Dr. Steven J. Schafrik, Department of Mining Engineering, University of Kentucky, January 2020 – December 2021.